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Final report

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Abstract: Risk assessment of contaminated sediments often involves quantification of compounds in tissues via laboratory bioaccumulation exposures of benthic invertebrates. However, the standard 28-day exposure duration may not be adequately long for some compounds to reach steady state, defined as a stable concentration in exposed organisms. Steady-state tissue residues can be estimated using uptake and elimination rate constants. Experiments were conducted using two marine sediments from New York Harbor to assess bioaccumulation of PAHs, PCBs, chlorinated pesticides, dioxins, and Hg by sampling tissue during seven successive time points over an exposure of 56 days for the polychaete worm *Nereis virens* and 119 days for the clam *Macoma nasuta*. Exposure time required to attain steady state was organism and compound specific. Generally, *N. virens* tissues reached steady state more rapidly and accumulated higher contaminant residues. *Nereis virens* attained apparent steady state within roughly 28 days for PAHs, Hg, and most PCBs, but longer exposure was needed for some dioxins and pesticides. Steady state in *M. nasuta* was generally attained after 28 days of exposure for most compounds (some times after 100 days). Thus, some 28-day tissue residues may underestimate bioaccumulation and subsequently risk to benthos and higher trophic level organisms. The results of this study allow development of site-specific correction factors for estimating steady-state residues from 28-day exposures.

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Preface

This report was prepared through a research effort funded by the U.S. Army Corps of Engineers (USACE) New York District. It describes the results of research focusing on the derivation of correction factors for assessing contaminant bioaccumulation in invertebrates using standardized sediment bioaccumulation bioassays as part of the USACE, North Atlantic Division, New York District (CENAN) dredging program.

The research effort was conducted at the U.S. Army Engineer Research and Development Center (ERDC) by Drs. Alan Kennedy, Guilherme Lotufo, Jeffery A. Steevens, and Todd S. Bridges, ERDC Environmental Laboratory (EL). Technical advice on this effort was provided by Monte Greges and Oksana Yaremko (CENAN). Analytical chemistry was completed by the analytical chemistry branch (Drs. Doug Taggert, Richard Karn, and Anthony Bednar). One contract laboratory, Test America (Knoxville, TN), participated in performing analytical chemistry services. The authors acknowledge support for this effort by Tom Wyche (CENAN) and Aqua Survey, Inc. (Flemington, NJ) with the collection of the sediments.

This report was prepared under the U.S. Army Corps of Engineers' Dredging Operations and Environmental Research Program, for which Dr. Todd S. Bridges serves as Program Manager. Dr. Mike Passmore was Deputy Director, EL, and Dr. Beth Fleming was Director, EL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

Executive Summary

The dredging of federal project canals throughout the United States is critical to meet shipping needs. Federal regulations require assessments of contamination and estimation of potential risk to aquatic life during the dredging, transport, and disposal of sediment. In addition to chemical analysis of the dredged material, biological testing of water column toxicity, sediment toxicity, and sediment bioaccumulation potential are employed to assist in estimating this risk. The following study was conducted to assess the adequacy of the standard bioaccumulation testing duration of 28 days (d) to approximate steady-state equilibrium in model test species for several classes of contaminants of concern in dredging projects. The steady-state tissue residue is the stable (usually maximal) concentration of contaminant in tissues achieved after adequately long exposure duration to allow full partitioning of contaminants from sediment. It is important for steady-state tissue residues to be properly determined to avoid underestimating risk. In this study, long-term bioaccumulation exposures were conducted using two commonly employed test organisms. The polychaete worm *Nereis virens* and the clam *Macoma nasuta* were exposed to two distinct sediments collected from the New York / New Jersey Harbor. Tissues were sampled at various time points to determine the uptake and elimination kinetics of multiple contaminant classes of concern (dichloro-diphenyl-trichloroethane (DDTs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), mercury, methyl mercury, dioxins, and furans). The uptake rates of chemicals into test organisms were directly measured and a kinetic model was used to indirectly determine elimination rates. This kinetics information was then used to derive useable information, such as the time (in days) required for analytes to reach steady state, the fraction of steady state acquired after the standard 28-d exposure duration and biota-to-sediment accumulation factors. Each of these parameters was specific to the chemical and test organism.

The *Macoma nasuta* clams generally took longer than the *Nereis virens* worms to reach stable tissue residues (i.e., the steady-state tissue residue). After 28-d exposure to the sediments, the *N. virens* achieved steady-state tissue residue (functionally defined as at least 80% of the actual equilibrium concentration) for most analytes, with the exceptions of DDTs and

a few dioxins and furans. The *M. nasuta*, however, achieved steady state only for PAHs and methyl mercury after 28 days of sediment exposure (and certain PCB, dioxin and furan congeners). While differences were observed in the clam uptake/elimination kinetics between the two test sediments, the authors concluded that the clam generally requires longer than 28 d (sometimes exceeding 100 d) to acquire steady-state tissue residues for mercury, DDTs, and most PCBs, dioxins, and furans. However, the contaminant levels in *N. virens* were greater than that of the clam, potentially making the worm the controlling factor for compliance comparisons to tissue residue benchmarks.

The data generated in this report support the hypothesis that 28-d exposure duration is adequate to estimate steady-state tissue residues for PCBs and many dioxins and furans in *N. virens*. This worm is not a good model species to determine the bioaccumulation potential of PAHs due to an efficient metabolism; *M. nasuta* or another inefficient metabolizer should be used instead. For *M. nasuta*, the 28-d exposure duration was not adequately long to allow this organism to reach stable concentrations for many of the analytes tested, although there were some discrepancies between the data acquired for the two sediments. The 28-d test duration was not adequately long for either organism to reach steady-state concentrations for DDTs. For analytes that reached steady state by 28 days of exposure, no further action or correction is necessary. However, for the analytes that do not reach at least 80% of steady state after 28 days of exposure, risk managers should consider application of organism and chemical-specific correction factors to estimate the steady-state tissue residues from values determined from the standard 28-d bioaccumulation tests. Such correction factors can be derived by taking the inverse of the fraction of steady-state values provided in this report, with the caveat that only two sediments were tested, and the cited literature (correction is acquired by the product of the 28-d tissue residue value and the correction factor). Recommended correction factors should be consolidated into a database to provide a toolbox for risk managers.

Unit Conversion Factors

Multiply	By	To Obtain
gallons (U.S. liquid)	3.785412 E-03	cubic meters

1 Introduction

The Clean Water Act (CWA) and Marine Protection, Research and Sanctuaries Act require assessment of potential adverse environmental impacts associated with open water placement of dredged material. The evaluation of dredged material proposed for disposal may require an assessment of bioaccumulation potential for benthic organisms using standard 28-day laboratory bioaccumulation procedures (e.g., U.S. Environmental Protection Agency (USEPA)/U.S. Army Corps of Engineers (USACE) 1991, 1998; American Society for Testing and Materials (ASTM) 2000). In these bioassays, model test organisms are exposed to sediments and the tissue residues of contaminants of concern are determined. This information is then used in predictive models. It is important that the duration of the bioaccumulation test is adequate to allow contaminants of concern in the sediment to reach stable concentrations in the test organisms, referred to as the steady-state concentration. Thus, the steady-state concentration is the tissue concentration of the test organism after adequately long exposure to test material to reach stable levels. It is an equilibrium that occurs when the flux of the chemical into the organism equals the flux of the chemical out of the organism. A hypothetical uptake curve is provided in Figure 1, illustrating the gradual increase in tissue residues over time. The plateau of this curve represents the steady-state condition.

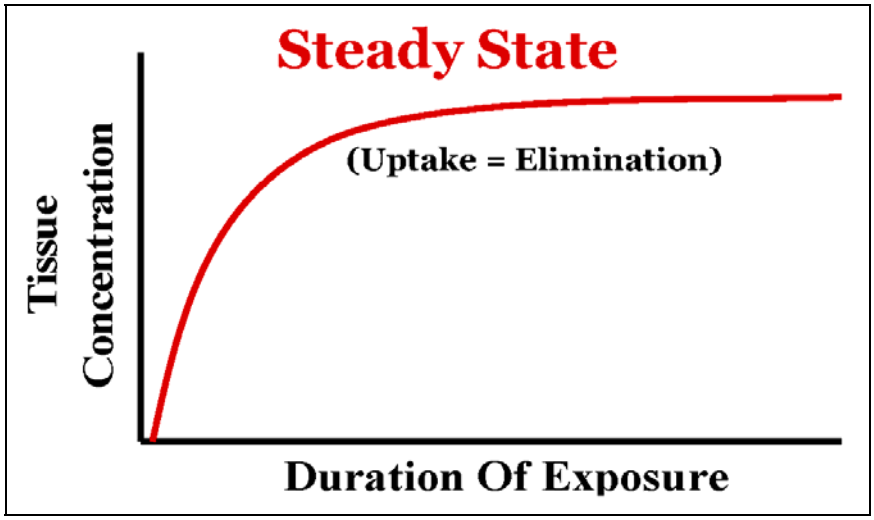

Figure 1. Hypothetical curve illustrating the uptake and subsequent stabilization of the concentration of a chemical in an organism exposed to contaminated sediment.

According to current guidance (USEPA/USACE 1991, 1998; ASTM 2000), at least 80% of the steady-state tissue residue of most compounds is expected at termination of a 28-d laboratory bioaccumulation test. However, the tissue residue of highly hydrophobic compounds ($K_{ow} > 5$) may not approach steady-state concentrations in some benthic invertebrates after the standard laboratory exposure duration of 28 d. When the tissue residues in bioaccumulation tests are not at steady state, test results are expected to underestimate tissue residues of invertebrates exposed to dredged material in the field. Bioaccumulation kinetics, and hence the time to steady state, in laboratory sediment bioassays are influenced chiefly by (1) size and physiology of the test species, (2) exposure conditions (e.g., temperature), (3) contaminant bioavailability and water/sediment conditions, and (4) chemical characteristics of the contaminant(s) of concern.

Various methods are available to determine steady-state tissue residues. The two used in this study were a kinetic-based approach and an operational approach. The kinetic-based method used direct measurements of chemical uptake and estimates of elimination rates that can be used in calculations to derive the time required to reach steady state and the steady-state tissue residue. The operational method simply applied statistical comparisons of tissue residues over time.

Currently, adjustments for chemicals in tissue residues that fall short of steady state after 28 d of exposure are applied in practice. Steady-state correction factors (SSCFs) are multipliers to approximate the steady-state condition from tissue residues obtained from a 28-d laboratory bioaccumulation test. When an adequate proportion of steady state is obtained (i.e., within 80% of actual equilibrium), no correction factor is needed. However, in cases where the steady-state concentration of an analyte is not reached after a 28-d bioassay, a correction factor is recommended to avoid underestimating risk. For instance, if 50% of steady state is obtained, tissue residues are multiplied by a correction factor of two to approximate the steady-state condition (i.e., a tissue residue of 100 µg/kg would be adjusted to 200 µg/kg). A factor of two is commonly applied to PCB tissues residues in the polychaete *N. virens* due to slow uptake rates reported in the literature (Pruell et al. 1990). For 2,3,7,8-TCDD, a factor of four has been suggested to adjust 28-d *N. virens* tissue residues to the steady-state concentration used in risk estimations while a factor of one (i.e., no correction) is used for the clam *M. nasuta* based on data from

Pruell et al. (1990). More recent work (e.g., Boese et al. 1995, 1996, 1997) reports a longer time period required for *M. nasuta* to reach steady state, implying that a correction factor greater than 1 is warranted. This report presents evidence that these correction factors are not necessarily applicable.

The objective of this study was to generate toxicokinetic information for a variety of contaminants of concern (i.e., PAHs, PCBs, chlorinated pesticides, mercury, methyl mercury, dioxins and furans) to be considered by the New York District dredging program. To derive these factors, two test organisms (*Nereis virens* and *Macoma nasuta*) were exposed to two distinct sediments collected from the New York/New Jersey Harbor in long-term bioaccumulation bioassays that involved analysis of tissue residues at various times over the course of the exposure. These data were used to derive toxicokinetic parameters (e.g., uptake and elimination rates, time required to reach steady state, steady-state concentrations, BSAFs) and compound- and species-specific factors for adjusting 28-d tissue residues to the steady-state residues.

2 Methods

Study sites

Approximately 110 gal of sediment was collected from each of two distinct sampling locations in the New York/New Jersey Harbor. Sediments were collected using a 2.5-gal Van Veen grab sampler and stored in 55-gal drums. The collection and sample storage methods followed USEPA (2001) guidance. Sediment from the first sample site was collected from Arthur Kill (40° 33.89' N, 74° 12.84' W) under supervision of the New York District and the U.S. Army Engineer Research and Development Center (ERDC) on 8 July 2004. The second sample site was Newark Bay (40° 39.74', 74° 9.36'), collected by Aqua Survey (Flemington, NJ) on 19 January 2005 (Figure 2).

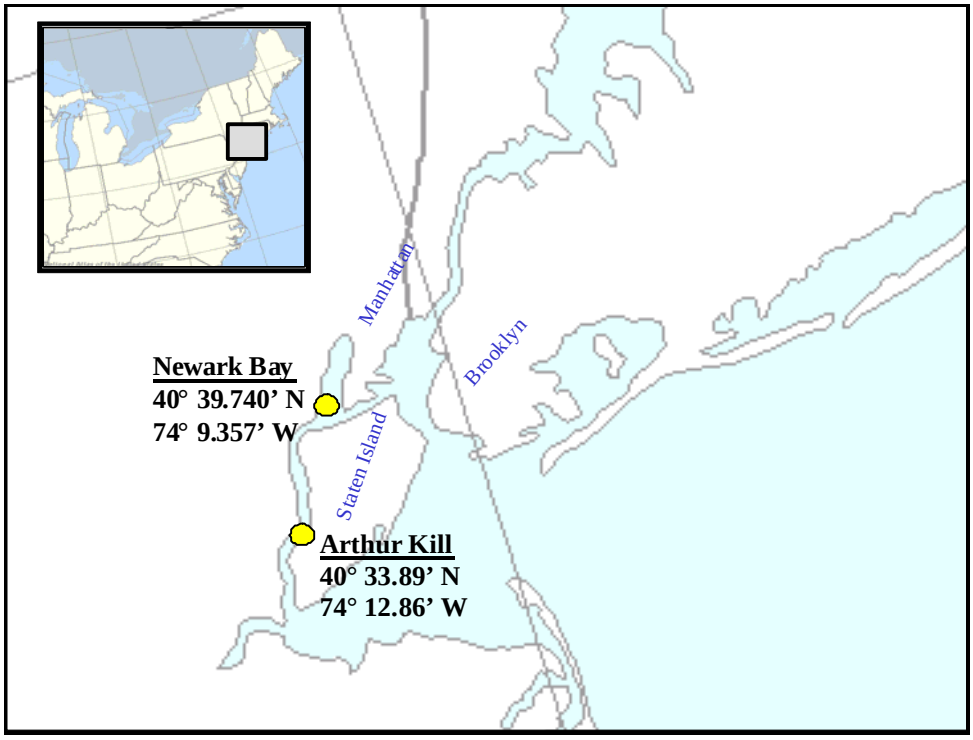

Figure 2. Sampling stations in New York Harbor.

Study organisms

The two benthic invertebrate test species selected for laboratory bio-accumulation tests are recommended in the Inland Testing Manual (USEPA/USACE 1998) and the Ocean Testing Manual (USEPA/USACE

1991) and used routinely in the North Atlantic Region. The polychaete worm *Nereis virens* is an active burrower (8–10 cm deep) and deposit feeder in sediment that efficiently metabolizes some hydrophobic organic contaminants such as PAHs (Ernst et al. 1977; Driscoll and McElroy 1996; Goerke and Weber 2001). The bent-nose clam *Macoma nasuta* is a facultative filter feeder that switches to deposit feeding in bioaccumulation tests due to low food concentration in the overlying water. *Macoma nasuta* metabolizes hydrophobic organic contaminants much less efficiently than *N. virens* (Rust et al. 2004). Both species, shown in Figure 3, were acquired from Aquatic Research Organisms (Hampton, NH). *Nereis virens* were collected from the Damariscotta River (Boothbay Harbor, ME, USA) and *M. nasuta* were collected from Tomales Bay (Dillon Beach, CA, USA).

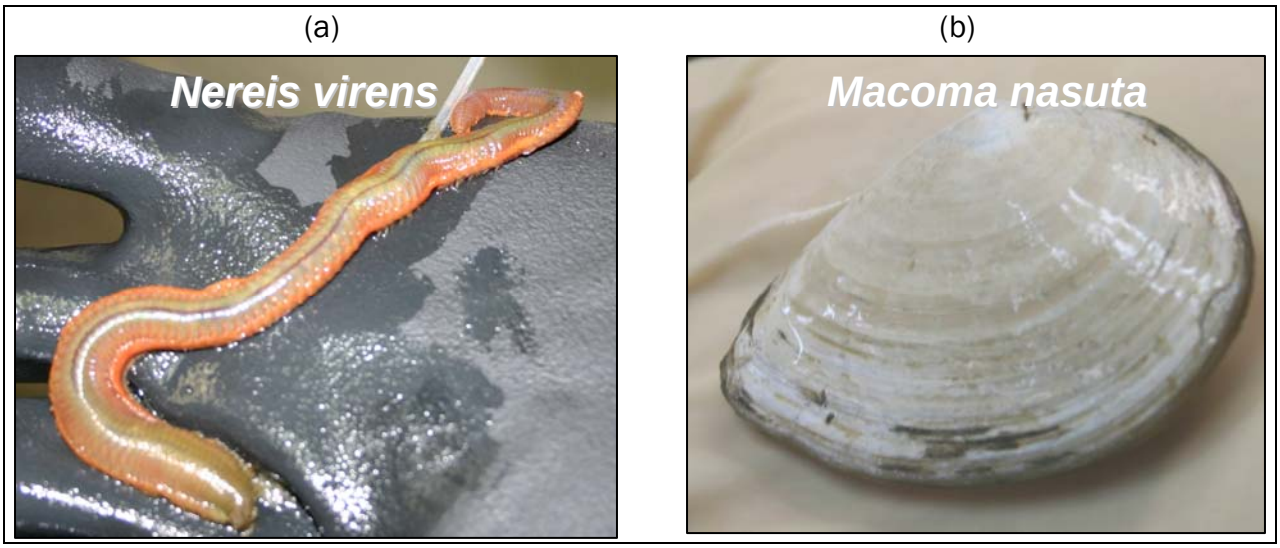

Figure 3. Benthic invertebrates used in sediment bioaccumulation tests. New York Harbor evaluations currently apply 28-d exposures using the polychaete worm *Nereis virens* (a) and the bent-nose clam *Macoma nasuta* (b).

Exposure design

The test methods generally followed those described in Appendix G of the Inland Testing Manual (USEPA/USACE 1998), with several modifications necessitated by (1) the study objective of assessing bioaccumulation duration exceeding 28 days, and (2) meeting the analytical tissue requirement of 23 g per exposure period (Table 1). Seven time points for sampling exposed tissue were selected based upon existing temporal patterns of bioaccumulation of hydrophobic compounds in the test species.

Table 1. Test conditions for the standard 28-d bioaccumulation tests (USEPA/USACE 1998) and the steady-state tests conducted in this study, modified from Lee et al. (1993).

Test method	Standard *Nereis virens*	This study *Nereis virens*	Standard *Macoma nasuta*	This study *Macoma nasuta*
Test type	Flow-through or Static Renewal	Static Renewal	Flow-through or Static Renewal	Static Renewal
Test duration	28 days	56 days	28 days	119 days
Temperature	10–20 °C	20 ± 1 °C	12–16 °C	15 ± 1.0 °C
Salinity	> 20 ‰	30 ± 2 ‰	> 25 ‰	30 ± 2 ‰
pH	7.8 ± 0.5	7.8 ± 0.5	7.8 ± 0.5	7.8 ± 0.5
Light quality	Ambient Laboratory	Ambient Laboratory	Ambient Laboratory	Ambient Laboratory
Light intensity	500 – 1000 ftc	500 – 1000 ftc	500 – 1000 ftc	500 – 1000 ftc
Photoperiod	16L:8D 14L:10D 12L:12D	16L:8D	16L:8D 14L:10D 12L:12D	16L:8D
Test chamber size	1L beaker or large aquarium	5-gal aquarium	250-mL beaker	5-gal aquarium
Loading	> 200 g sediment/ g wet tissue	> 200 g sediment/ g wet tissue	> 200 g sediment/ g wet tissue	> 200 g sediment/g wet tissue
Sediment depth	> 4 cm	> 4 cm (3 L in 5 gal tank)	> 50 g sediment / g tissue (w/w wet)	> 200 g sediment/g (5 L in 5-gal tank)
Renewal of test solution	Flow through (5–10 v/d) Static renewal (3x/wk)	Static renewal (1x/day)	Flow through (5–10 v/d) Static renewal (3x/wk)	Static renewal (1x/day)
Size/Age of test organisms	3–15 g	3–7 g	2–4 yr old (shell: 28–45 mm)	2–4 yr old (shell: 28–45 mm)
No. of test organisms	1 per beaker 20 per 20-gal aquarium	10 per 5-gal aquarium	1 / beaker	15–20 / aquarium
Replicates/ sediment	5–8	7 time points 3 replicates	5–8	7 time points 3 replicates
Feeding	None	None	None	None
Aeration	Moderate	Moderate	Moderate	Moderate
Dilution water	Natural or reconstituted seawater	Instant Ocean® seawater	Natural or reconstituted seawater	Instant Ocean® seawater
Treatments	Control, reference, site sediment	3, 7, 14, 21, 28, 42, 56 days exposure	Control, reference, site sediment	5, 10, 28, 42, 60, 90, 119 days exposure
Dilution series	NA	NA	NA	NA
Endpoint	Bioaccumulation	Bioaccumulation	Bioaccumulation	Bioaccumulation
Sampling/holding time	< 8 weeks	< 8 weeks	< 8 weeks	< 8 weeks
Test acceptability	Adequate tissue mass for analysis	23 g tissue	Adequate tissue mass for analysis	23 g tissue

For *N. virens*, tissue residues were assessed after 3, 7, 14, 21, 28, 42, and 56 days while *M. nasuta* residues were assessed after 5, 10, 28, 42, 60, 90, and 119 days of exposure. Each time point consisted of three replicate 5-gal aquaria containing site sediment (3 L for *N. virens* and 5 L for *M. nasuta*) at a wet sediment-to-tissue ratio exceeding 250 g of sediment per g of tissue as recommend by Lee et al. (1993). Aquaria were filled with 30 ‰ Instant Ocean Seawater (Aquarium Systems, Inc., Mentor, OH) and sediment was allowed to settle overnight.

Test temperature and photoperiod were regulated using water baths equipped with timer-controlled lights and water re-circulating REMCOR heating/cooling units (REMCOR Products Company, Glendale Heights, IL). The *N. virens* and *M. nasuta* exposures were initiated concurrently for the Arthur Kill sediment (August 3, 2004) and the Newark Bay sediment (February 10, 2005). The exposures were conducted under static-renewal conditions with 60% of the overlying water replaced daily for the duration of the experiments. To reduce the depletion of target analytes over the extended exposure duration, test sediment was completely renewed every 30 days by transferring live organisms to new tanks containing fresh sediment. Water quality parameters were monitored each weekday in at least one aquarium per species per time point.

Temperature was maintained at 20 ± 1 °C for *Nereis virens* and 15 ± 1 °C for *M. nasuta*. Exposure chambers received aeration via air stones. The quality of the overlying water was monitored using a model ABMTC hand-held refractometer (Aquafauna Bio-Marine, Hawthorne, California) for salinity, a model 315i meter (WTW; Weilheim, Germany) for pH, and a model Oxi 330 meter (WTW; Weilheim, Germany) for D.O. Porewater ammonia samples were taken by centrifuging 45 mL of sediment at 2,700 g for 15 minutes using VWR Brand 50 mL centrifuge tubes (Cat. No. 21008-177). The porewater, or supernatant, was then decanted and analyzed for total ammonia concentrations using an 720A ion selective electrode (ISE) meter (Thermo Orion Electron Corp., Beverly, MA) equipped with a 95-12 ammonia sensitive electrode (Thermo Orion Electron Corp., Beverly, MA).

Test organisms with a combined mass of approximately 25 g wet weight were added to each replicate aquarium. The mean wet mass of the *N.*

virens worms tested was 4.55 (2.50 – 6.59)[1] g while the mean wet mass of whole *M. nasuta* clams was 10.96 (7.65 – 14.28)[1] g. To estimate the number of *M. nasuta* specimens required to equal 25 g, 10 clams were selected for sacrifice and their whole weights (tissue and shell) and dissected wet tissue weights were used to derive a whole clam to wet tissue conversion factor of 0.18. Thus, whole live organisms were weighed prior to their addition into aquaria and this conversion factor was applied to the whole clam weight. Therefore the mean wet tissue mass of *M. nasuta* used in experimentation was 1.97 (1.34 – 2.57) g. Test organisms failing to burrow after 30 min (*N. virens*) or 4 hr (*M. nasuta*) were promptly replaced.

At the termination of each time point, test organisms in the three replicated exposure aquaria were removed from the sediment and rinsed. Undigested sediment was removed from the gut of test organisms prior to analysis of tissue residues. *Nereis virens* was anesthetized in an isotonic $MgCl_2$ solution and undigested sediment was pushed from the gut by gentle compression using a clean stainless steel spatula from anterior to posterior. Clam tissue was removed from the shells, the gut was dissected with a scalpel, and contents were rinsed away using DI water. Organisms were then thoroughly rinsed with DI water, blotted dry, weighed, and frozen at -80 °C. Organism tissue from each replicate was composited and homogenized by pulverization using a mortar and pestle over liquid nitrogen until ground into a powder (Boese et al. 1995). Pulverized tissue from each replicate was then weighed into separate scintillation vials for each chemical class and submitted for chemical analysis.

Analytical chemistry

Each of the homogenized sediments / tissues was sampled for chemical analysis and submitted to the U.S. Army ERDC-EL Environmental Chemistry Branch (Vicksburg, MS) for analysis of pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), total metals, simultaneously extracted metals (SEM), and acid volatile sulfides (AVS). Samples were submitted to Severn Trent Laboratories (Knoxville, TN) for dioxins and furans. All chemical analyses followed U.S. EPA 846 methodology. Organic compounds were extracted by method 3545 using accelerated solvent extraction. Cleanup of organic extracts was accomplished for PAHs using a modification of method 3630 (silica gel), for pesticides using a modification of method 3630 (florisil), and for PCBs

[1] 99% confidence intervals.

using a modification of method 3665 (sulfuric acid). PAH analysis was according to method 8270 by gas chromatograph using selective ion monitoring mode. Pesticides and PCBs were analyzed using an Agilent 5890 gas chromatograph with electron capture detection. Metals were analyzed following methods 6010B and 6020 using a Perkin Elmer Optima 3000DV Inductively Coupled Plasma Atomic Emission Spectrometer and Elan 6000 Inductively Coupled Plasma Mass Spectrometer, respectively. Total mercury analysis was performed using a P.S. Analytical Atomic Fluorescence Detector following method 7471A. Methylmercury was determined using ethylation followed by carbon-trapping and analysis by gas chromatography with fluorescence detection. Dioxins and furans were measured using method 8290 by high-resolution gas chromatograph — mass spectrophotometry. Grain size distribution of sediments was determined using ASTM method D422.

The target analytical tissue requirement for dioxins/furans, PCBs, PAHs, and chlorinated pesticides was 5 g while for mercury and methyl mercury the requirement was 1 g. In some cases the target weight was not achieved (always > 3.5 g) with the exception of dioxins and furans where 5 g was always achieved. Lipid analysis was conducted using a method modified from Van Handel (1985). Tissue samples (whole individual worms) were homogenized in 1.5 ml of chloroform/methanol (1:1 v/v). Homogenates were transferred to 13- × 100-mm tubes and centrifuged for 10 min at 1000 g. After recording the total volume, 0.25 ml of the supernatant was transferred to a new 13- × 100-mm tube and placed in a heating block at 100 °C until all the solvent had evaporated. Concentrated sulfuric acid (0.2 mL) was then added and the tubes were reheated at 100°C for 10 min. After cooling, 4.8 ml of vanillin reagent was added. Vanillin reagent was prepared by dissolving 600 mg of vanillin (Sigma, St. Louis, MO, USA) in 100 mL of hot water and adding 400 mL of 85% phosphoric acid. After 5 min, samples were read in a spectrophotometer at 490 nm against a reagent blank. Lipid content was derived from a calibration line obtained using standards of 0, 100, 250, 500, 1000, and 1500 µg of soybean oil (Sigma, St. Louis, MO, USA) and the procedure described above. The supernatant volume was multiplied by the mass of lipid determined from the standard curve (yielding mg lipid), and then divided by the sample weight (in mg) and multiplied by 100 to obtain the percent lipid value.

Data analysis

Tissue residues for all three replicates within each time point were plotted using SigmaPlot® software (SPSS, Chicago, IL) applying the user-defined option and the following non-linear one-component-uptake equation from ASTM (2000):

$$C_{tissue} = \left(\frac{k_s * c_s}{k_e} \right) \left(1 - e^{-k_e * t} \right) \quad (1)$$

where:

k_s (aka k_1 or k_u) = uptake rate constant from sediment to the organism (expressed in g/g/d)
k_e (aka k_2) = elimination rate constant from the organism (expressed as 1/t)
c_s = contaminant concentration in sediment
t = time in days.

This equation was used to directly measure the uptake rate (k_s) while the elimination rate (k_e) was estimated using the same uptake curve. Some individual replicates were discarded (> 2 S.D. from the mean) as obvious outliers.

The time required to reach 95% of steady state ($TSS_{95\%}$), in days, was determined using the following equation from ASTM (2000):

$$\mathrm{TSS}_{95\%} = \frac{Ln\left(\frac{1}{1 - 0.95} \right)}{k_e} = \frac{3}{k_e} \quad (2)$$

Both 95% and 80% steady state will be referenced later in this report. The equation above determines the time the exposed test subject requires to approximate steady-state tissue residues. However, according to guidance (USEPA/USACE 1991, 1998; ASTM 2000), 28-d sediment bioaccumulation tests that obtain at least 80% of steady state are acceptable for use in risk calculations. Therefore, although the amount of time needed to approximate steady state (95%) is reported, the data set to 80% of steady state is used in determining whether the 28-d exposure duration is adequate for each analyte of concern.

In addition, the fraction of steady state (f_{ss}) acquired after 28 days was obtained from an equation supplied by McFarland (1995):

$$f_{ss} = 1 - e^{-k_e * 28} \tag{3}$$

The steady-state correction factors (SSCF) can be determined by taking the inverse of f_{ss}.

$$\text{SSCF} = \frac{1}{f_{ss}} \tag{4}$$

The biota-to-sediment-accumulation factor (BSAF) for each analyte was determined as follows:

$$\text{BSAF} = \frac{c_t / L}{c_s / OC} \tag{5}$$

where:

c_t = concentration in the tissue
L = lipid fraction
c_s = concentration in the sediment
OC = organic carbon fraction of the sediment.

BSAFs were determined from both 28-d tissue residues ($BSAF_{28d}$) and steady-state tissue residues ($BSAF_{SS}$).

The steady-state concentration for each analyte was determined using two methods. A kinetic calculation was employed by inputting the TSS into Equation 1 as "t." In addition, an operational approach for estimating steady state was used; this method defines steady state as the mean tissue concentration between three consecutive and statistically indistinguishable time points (Boese et al. 1995; ASTM 2000); this method can be used to estimate steady-state tissue residues in the absence of kinetic information. All statistical comparisons used the SigmaStat® software package (SPSS, Chicago, IL). The Holm-Sidak Test was used as recommended for an initial screen, as it is more powerful than the Tukey and Bonferroni tests. Uncertainty (including error bars) for these measures (Equations 2 and 3) was determined by inserting $k_e \pm$ the standard error obtained from the model (Equation 1) into the equations above.

3 Results and Discussion

Sediment chemistry

Sediment chemistry results were summed for each chemical class and are provided in Table 2 to roughly compare the relative contamination of the two test sediments. Full data reporting is provided in Appendix A. In general, the contamination levels and organic carbon content were similar between sediments, although chlorinated pesticides were below detection limits in the Newark Bay sediment.

Table 2. Summary of concentrations of general chemical classes in the Arthur Kill and Newark Bay sediments used in this study.

Sediment	TOC (%)	Black Carbon (%)	Adjusted TOC (%)	Σ PAH (µg/kg)	Σ PCBs (µg/kg)	Σ DDT (µg/kg)	Σ Dioxins (µg/kg)	Mercury (µg/kg)	Methyl Mercury (µg/kg)
Arthur	2.9	0.15	2.7	11,938	153	439	3.9	4.68	43.1
Newark	2.2	0.12	2.1	8,033	156	ND	2.1	2.55	2.75

Water quality parameters

Water quality ranges measured during the 28-d bioaccumulation bioassays met the specifications of protocols (USEPA/USACE 1998) for temperature, dissolved oxygen, and pH (Table 3).

Table 3. Summary of mean water quality parameters (± one standard deviation), with minimum and maximum values in parentheses, for bioaccumulation exposures conducted in this study.

Test Organism	Sediment	Temperature (°C)	Salinity (‰)	pH (SU)	D.O. (mg/L)
Nereis virens	Arthur	19.4 ± 0.8 (17.4 – 21.0)	30 ± 1 (29 – 34)	8.11 ± 0.12 (7.79 – 8.33)	6.88 ± 0.55 (5.51 – 8.06)
	Newark	19.2 ± 0.4 (18.2 – 20.1)	32 ± 1 (30 – 33)	8.16 ± 0.08 (7.98 – 8.30)	8.49 ± 0.88 (5.32 – 9.50)
Macoma nasuta	Arthur	15.8 ± 0.3 (14.9 – 16.6)	30 ± 1 (29 – 34)	8.10 ± 0.08 (7.89 – 8.27)	6.90 ± 0.88 (4.10 – 7.99)
	Newark	15.6 ± 0.4 (14.3 – 16.3)	31 ± 1 (30 – 33)	8.10 ± 0.08 (7.89 – 8.30)	9.16 ± 0.64 (5.78 – 10.10)

Lipid content

No apparent trend was observed for mean lipid content of *N. virens* and *M. nasuta* during the exposures (Figure 4). The mean lipid content for *N. virens* on a wet weight basis was 1.8 ± 0.3% (10.2 ± 1.77% dry weight basis) for the Arthur Kill exposure and 1.7 ± 0.2% (10.0 ± 1.2% dry weight basis) during the Newark Bay exposure, which were higher relative to dry weight based values of 7.6% to 8.3% obtained from the literature (Pruell et al. 1990; Schrock et al. 1997). McLeese et al. (1980) reported wet weight lipid contents for *N. virens* of 1.3 % (0.6–1.7%). The mean lipid content for *M. nasuta* on a wet weight basis during the exposures to Arthur Kill and Newark Bay sediments of 1.3 ± 0.1% (7.3 ± 0.6 dry weight basis) and 1.1 ± 0.1% (6.2 ± 0.6% dry weight basis), respectively, were comparable to range of 1.0–2.8 % reported in a previous study (McFarland et al. 1994).

Bioaccumulation kinetics

Toxicokinetic parameters were only derived for analytes with uptake curves that fit the nonlinear model with a significance level of $p \leq 0.10$. For analytes that were consistently detected in tissue but no temporal trend in the uptake curve was apparent (e.g., PAHs in *N. virens*), steady state was assumed during or prior to early time points. While the uptake and apparent elimination kinetics for *N. virens* were similar in both sediment exposures (Appendix B), faster kinetics were observed in *M. nasuta* for some analytes (PCBs, dioxins, furans) in the exposure to Newark Bay sediment (Appendix C). Generally, uptake and elimination rates were slower for *M. nasuta* than for *N. virens*. Thus, the clam typically required more time than the polychaete to reach steady-state tissue residues. An example of this is illustrated for TCDF (Figure 5). At day 28 of the sediment exposure, 41 of the 73 analytes modeled did not reach 80% the estimated steady-state tissue residue for *M. nasuta*, while only 39 of the 63 analytes modeled were below that level for *N. virens*. Fewer analytes were modeled for *N. virens* because of lack of detection in tissues. The percent of steady state obtained after *N. virens* and *M. nasuta* were exposed to the two test sediments for 28 days is summarized in Table 4. While *N. virens* was generally faster to steady state than *M. nasuta*, its tissue residues were as much as two-fold higher in the polychaete during most time points. This may be partially explained by the lipid content of the polychaete being 1.4 times greater than that of the clam, an explanation also used by Pruell et al. (1990). While the data set suggests *M. nasuta*

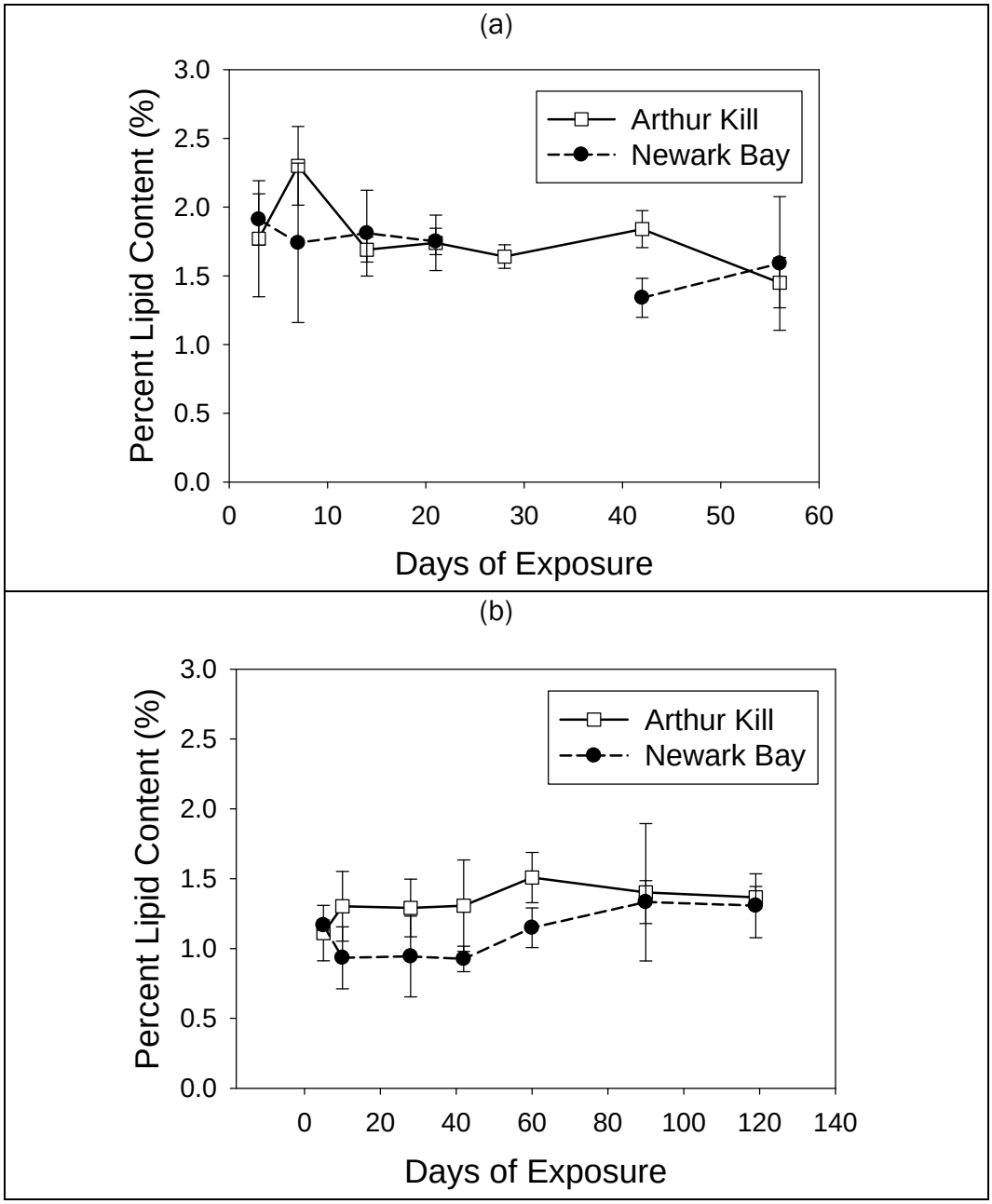

Figure 4. Percent lipid content for *Nereis virens* (a) and *Macoma nasuta* (b). No consistent statistically significant trends were observed over time for *N. virens*, while no statistical significance between time points was observed for *M. nasuta*.

is more likely to require steady-state correction factors following 28 days of exposure, the higher tissue residues (at steady state) obtained for *N. virens* suggest this species may frequently exceed tissue benchmarks in dredging evaluations.

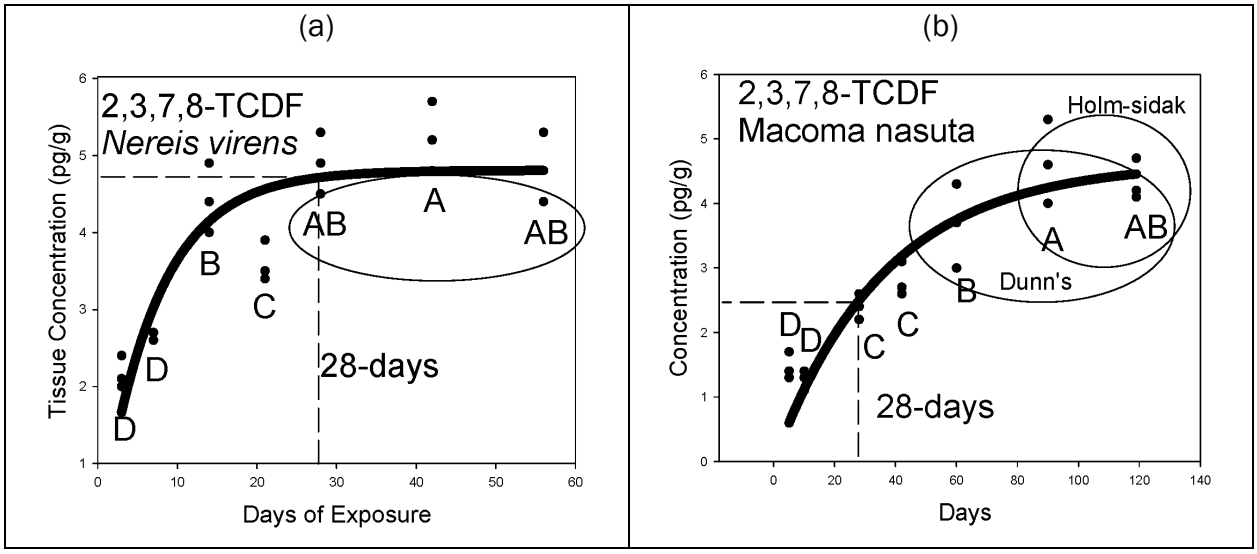

Figure 5. 2,3,7,8 TCDF uptake curves for *Nereis virens* (a) and *Macoma nasuta* (b). The curves graphically indicate that while 28 days was adequate for steady-state tissue residues in *N. virens*, more time was needed for *M. nasuta.* The dashed line indicates the concentration after 28 days of exposure. Time points with the same letter designation were not statistically different from one another according to the Holm-Sidak (or Dunn's) test. The circled data points indicate the first set of three consecutive time points that are not statistically different, indicating steady state by the operational method.

Table 4. Percent of steady state obtained for analytes of concern after the standard laboratory exposure of 28 days (80 percent of steady state is considered acceptable by guidance).

	Percent of Steady State at 28 days			
	Nereis virens		*Macoma nasuta*	
Compounds	Arthur	Newark	Arthur	Newark
Pesticides				
2,4-DDD	70	NA	62	NA
2,4-DDE	77	NA	60	NA
2,4-DDT	<DL	<DL	<DL	<DL
4,4-DDD	61	NA	63	NA
4,4-DDE	87	NA	50	NA
4,4-DDT	56	NA	58	NA
Total DDT	63	NA	56	NA
PCBs				
8	<DL	<DL	85	<DL
18	100*	99	ND	100
28	99	96	76	99
44	98	89	39	98
49	100	90	45	99
52	98	89	75	98
66	<DL	85	<DL	97
77	<DL	<DL	<DL	<DL

Compounds	Percent of Steady State at 28 days			
	Nereis virens		*Macoma nasuta*	
	Arthur	Newark	Arthur	Newark
PCBs (cont)				
81	<DL	<DL	<DL	<DL
87	<DL	<DL	<DL	<DL
101	93	82	51	97
105	83	88	74	96
114	<DL	<DL	<DL	<DL
118	90	84	19	92
123	<DL	<DL	<DL	<DL
126	<DL	<DL	<DL	<DL
128	90	100*	74	100*
138	94	90	53	96
156	<DL	<DL	<DL	<DL
157	<DL	<DL	<DL	<DL
167	<DL	<DL	<DL	<DL
169	<DL	<DL	<DL	<DL
170	91	100	100*	<DL
180	87	90	55	99
183	88	100	100	<DL
184	<DL	<DL	<DL	<DL
187	<DL	92	ND	100
189	<DL	<DL	<DL	<DL
195	<DL	<DL	<DL	<DL
206	100*	ND	<DL	<DL
209	<DL	<DL	<DL	<DL
PAHS				
Acenaphthene	<DL	<DL	<DL	<DL
Acenapthylene	<DL	<DL	<DL	<DL
Anthracene	<DL	<DL	<DL	<DL
Benzo[a]anthracene	<DL	<DL	100*	96
Benzo[a]pyrene	<DL	<DL	<DL	98
Benzo[b]fluoranthene	<DL	<DL	59	99
Benzo[g,h,i]perylene	<DL	<DL	<DL	<DL
Benzo[k]fluoranthene	<DL	<DL	<DL	100
Chrysene	<DL	<DL	47	92
Dibenzo[a,h]anthracene	<DL	<DL	<DL	<DL
Fluoranthene	100	100*	93	99
Fluorene	<DL	<DL	<DL	<DL

Compounds	Percent of Steady State at 28 days			
	Nereis virens		*Macoma nasuta*	
	Arthur	Newark	Arthur	Newark
PAHS (cont)				
Indeno [1,2,3-c,d]pyrene	<DL	<DL	<DL	<DL
Naphthalene	<DL	<DL	<DL	<DL
Phenanthrene	<DL	<DL	<DL	100*
Pyrene	100	100	69	99
DIOXINS/FURANS				
2,3,7,8,-TCDD	72	82	44	78
Total TCDD	94	77	33	88
1,2,3,7,8-PeCDD	<DL	<DL	100*	<DL
Total PeCDD	ND	ND	ND	ND
1,2,3,4,7,8-HxCDD	<DL	<DL	<DL	<DL
1,2,3,6,7,8-HxCDD	88	75	72	66
1,2,3,7,8,9-HxCDD	<DL	<DL	100*	<DL
Total HxCDD	91	89	ND	75
1,2,3,4,6,7,8-HpCDD	99	100	61	57
Total HpCDD	98	ND	39	38
OCDD	99	100*	51	62
2,3,7,8-TCDF	98	100	54	ND
Total TCDF	100	96	34	89
1,2,3,7,8-PeCDF	69	92	60	<DL
2,3,4,7,8-PeCDF	75	96	76	94
Total PeCDF	94	98	ND	87
1,2,3,4,7,8-HxCDF	100	100	88	85
1,2,3,6,7,8-HxCDF	97	100*	ND	<DL
1,2,3,7,8,9-HxCDF	<DL	<DL	<DL	<DL
2,3,4,6,7,8-HxCDF	ND	100*	82	<DL
Total HxCDF	ND	100*	59	85
1,2,3,4,6,7,8-HpCDF	100	97	ND	54
1,2,3,4,7,8,9-HpCDF	<DL	100*	ND	<DL
Total HpCDF	100	100*	76	59
OCDF	98	100*	45	41
METALS				
Mercury	100	100*	63	72
Methyl mercury	100	100*	100*	95

ND = could not be determined

<DL = not detected in tissues (latter time points)

* = Steady state obtained based on visual determination (curve fit not significant)

Steady-state determination: Kinetic vs. operational methods

The operational method for determining steady state was inconsistent for all chemical classes and subject to (1) how the definition was interpreted (i.e., mean of first three or last three consecutive statistically similar time points), and (2) testing artifacts such as inter- and intra-time point variability, spread of the time points (e.g., 3, 7, 14 days vs. 5, 10, 28 days), selection of statistical analysis method and analytical detection limits. To illustrate potential uncertainties associated with the operational method, the results derived using the kinetic and operational methods were compared for *N. virens* exposed to DDTs (Appendix D1). In many cases, determining steady state by the operational method was altered if the first three or last three consecutive statistically indistinguishable data points were selected. If the first three points were selected, the operational method provided an estimated steady-state concentration that was sometimes but not always (e.g., p,p-DDT) lower than that of the kinetic method (Equations 1 and 2). In some cases, the 3-, 7-, and 14-day (e.g., p,p-DDE) or 21-, 28-, and 42-day (e.g., p,p-DDT) time points were statistically similar while simple examination of the graph indicated that there was still an increasing, albeit gradual, trend in uptake in later time points (i.e., 42 and 56 days). When the last three statistically similar data points were used, the operational method provided steady-state concentrations similar to those of the kinetic method (within 10−20% error). The use of the operational method, however, is problematic when the exposure duration of an experiment is not long enough for tissue residues to reach stable concentration. The operational method is greatly influenced by (1) variability within and between time points, (2) gradually increasing trends (i.e., means are too close to elicit statistical differences), and (3) time points that are sampled too closely together. In these cases, the steady-state concentration would be underestimated. Similar conclusions were inferred from the *M. nasuta* exposure (Appendix E1). The subjectivity of applying this method is exacerbated by the lack of clear guidance on which statistical method (e.g., t-tests, one way ANOVAs with Tukey's method) to use. Differences in the analysis outcome are reported in Appendix D1, where more conservative (Tukey) and more powerful (Holm-Sidak) statistical methods were applied to the same data sets.

Overall, it is clear from this analysis that the kinetic method for determining steady state is preferable and more versatile. It does not have the same limitations as the operational method and can extrapolate beyond the actual test duration to estimate steady state, including additional

parameters such as time to steady state (TSS) and fraction of steady state (f_{ss}). Additionally, the kinetic method provides a more robust measure of variability (e.g., k_u, k_e with standard errors) that can be propagated through uptake and food web models. The operational method could be useful when the kinetic method cannot be applied due to insignificant curve fitting after visual inspection of the curve to ensure the results of the statistical comparison are logical. Because of the uncertainties associated with the operational method, the steady-state parameters (e.g., time to steady state, fraction of steady state) were determined by the kinetic method in the results and discussion sections below.

Chlorinated pesticides

Pesticide sediment chemistry (Table A1), kinetics information (Tables B1 and C1), and uptake curves (Figures D1 and E1) are summarized in detail in the appendices.

Data were obtained for DDTs[1] only in the exposures to the Arthur Kill sediment, since the Theoretical Bioaccumulation Potential (TBP) model (USEPA/USACE 1998) indicated that other chlorinated pesticides in the Arthur Kill sediment and all pesticides in the Newark Bay sediment would be below detection limits in tissues. Overall, data obtained from this study and the available literature (e.g., Boese et al. 1997) indicate that the standard 28-d test duration was inadequate for DDTs to achieve the requirement of at least 80% of the steady state in both *N. virens* and *M. nasuta*. Thus, use of SSCFs for 28-d tissue residues for DDTs is recommended.

The uptake rates for DDTs were much higher in *N. virens* (0.007 - 0.0111 g/g/d) than in *M. nasuta* (0.0009–0.0048 g/g/d), resulting in faster acquisition of steady state. Except for p,p'-DDT, the rates for *M. nasuta* were much lower in exposures to Arthur Kill sediment than rates determined for clams (0.012–0.038 g/g/d) exposed to DDT-spiked sediments from the Lauritzen Channel (Richmond, CA) (Boese et al. 1997) (Figure 6). The higher uptake rates from the Boese et al. (1997) study are likely an artifact of sediment spiking resulting in increased bioavailability. The uptake rates for p,p'-DDT were substantially lower than for other DDTs in both this study and in the study by Boese et al. (1997). Studies reporting uptake rates for DDTs in *N. virens* from sediment were not found in the peer-reviewed literature.

[1] Represents dichlorodiphenyltrichloroethane (DDT), dichlorodiphenyldichloroethylene (DDE), and dichlorodiphenyldichloroethane (DDD).

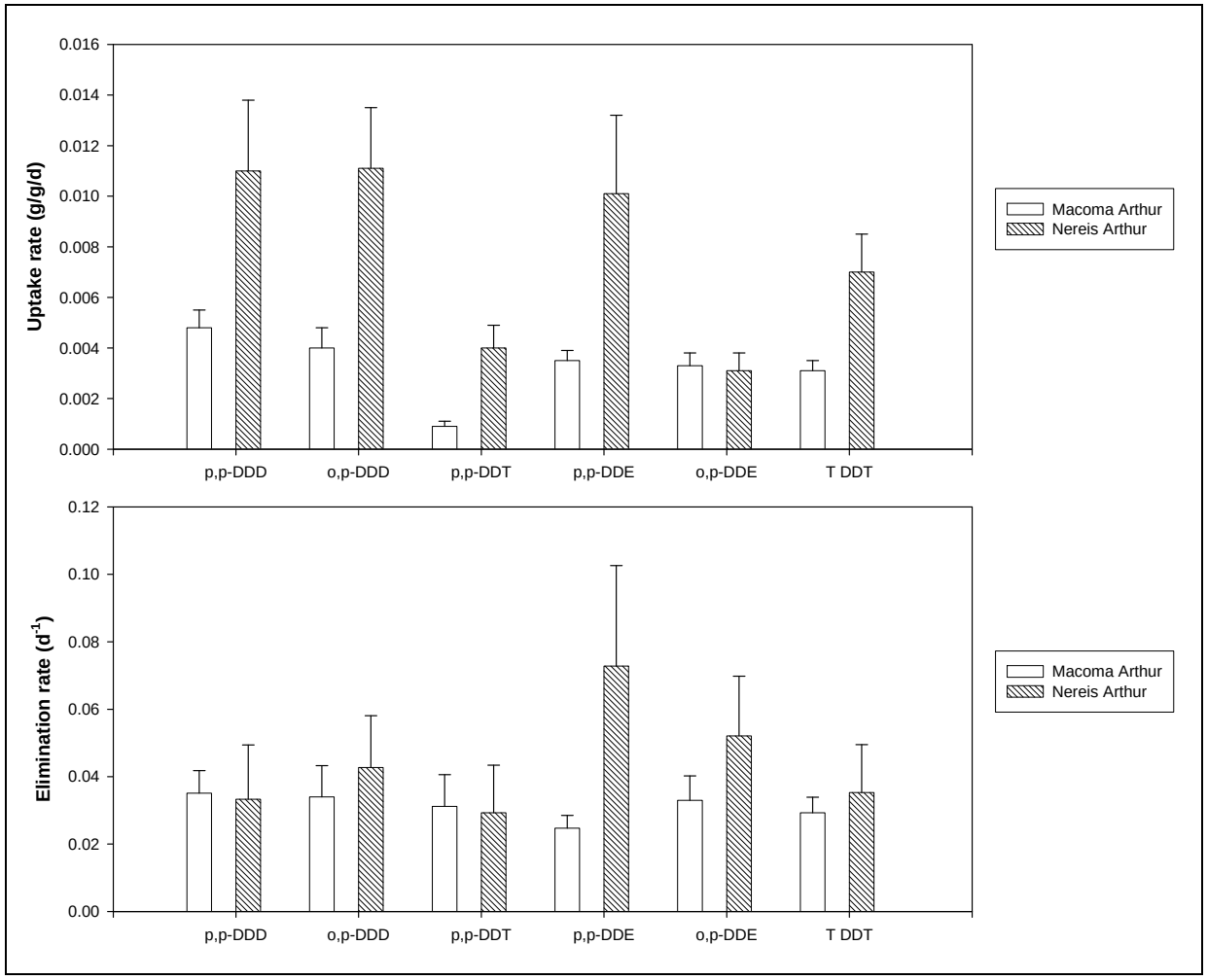

Figure 6. Uptake (a) and elimination rates (b) for DDT analytes and sum of all DDTs derived in this study for *Macoma nasuta* and *Nereis virens* exposed to Arthur Kill sediment.

DDT elimination rates between species were similar, although relatively higher for *N. virens* (0.0293–0.728 d^{-1}) than in *M. nasuta* (0.0247–0.0351 d^{-1}) (Figure 6b). The elimination rates modeled from the uptake curve for *M. nasuta* were comparable to those determined for clams exposed to sediments from the Lauritzen Channel (Boese et al. 1997) using the same method (Figure 7). Studies of the elimination of DDTs in *N. virens* after sediment exposure were not found in the available literature. Haya and Burridge (1988) conducted a study examining the uptake and elimination kinetics of *N. virens* from water exposures under both normal and suboptimal oxygen conditions and reported comparable elimination values ranging from 0.001 to 0.002 h^{-1} (or 0.024 – 0.048 d^{-1}) for worms exposed to normal oxygen conditions.

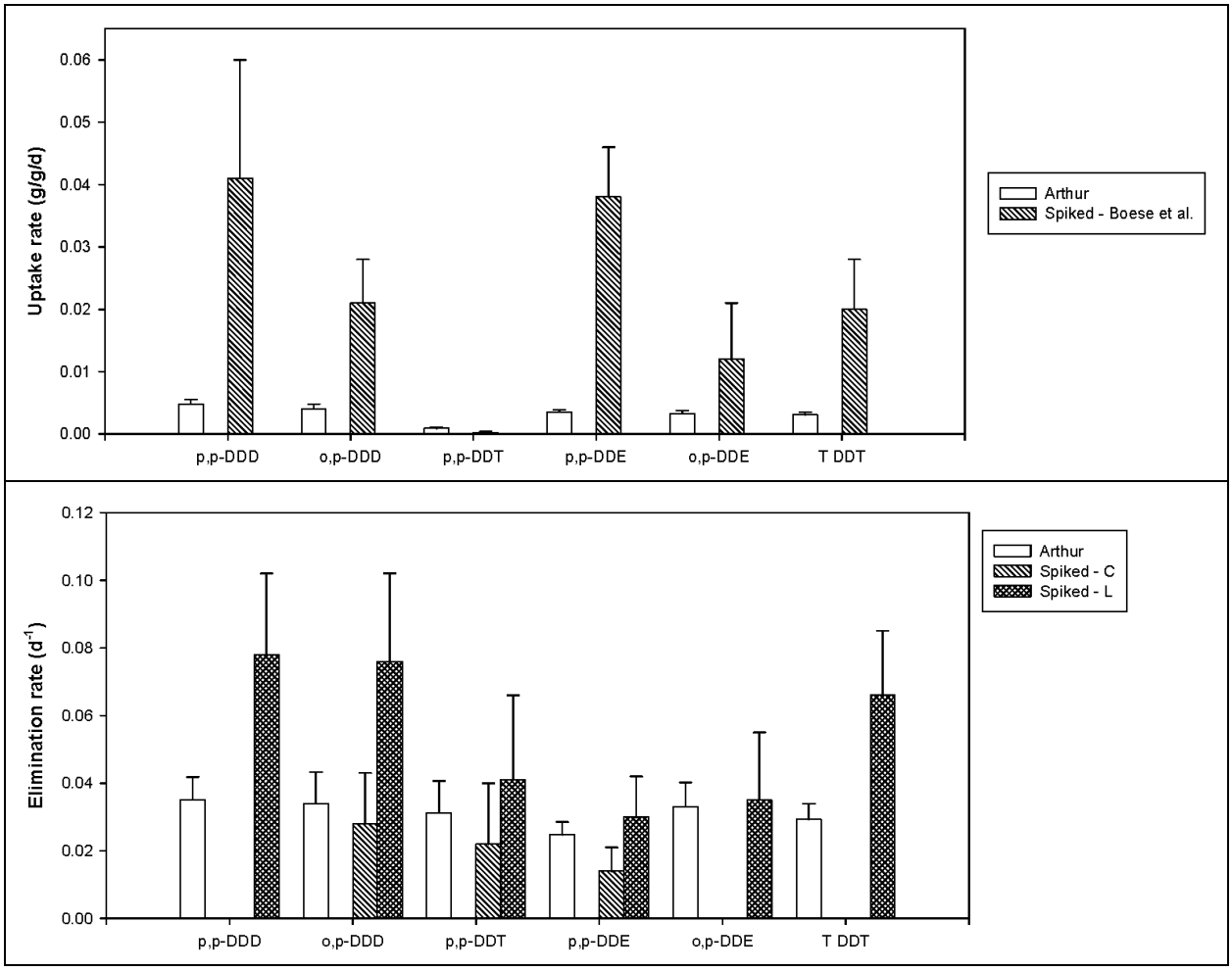

Figure 7. Uptake and elimination rates for *Macoma nasuta* exposed to DDT analytes and sum of all DDTs for this study (Arthur Kill sediment) and the Lauritzen Channel (Boese et al. 1997). Boese measured elimination rates by two methods: (1) by estimates derived from curve fitting (Spiked - C), as in this study, and (2) by direct measurement of linear uptake and elimination (Spiked - L).

For *N. virens*, steady state (as determined from Equation 2) for the DDTs was approached between 41 and 102 days, depending on the analyte. When tissue residues for all DDTs were summed (total or ΣDDTs), steady state occurred after 85 days of exposure. The only analyte to reach the guidance requirement (i.e., at least 80% of steady state after 28-d exposure) was p,p-DDE. Tissue residues were only 56 to 77% of steady state for the other analytes after 28 days of exposure. The time periods required for DDTs to approach steady-state tissue residues in *Macoma nasuta* (86–122 days) were longer overall than those determined for *N. virens*. For ΣDDTs, steady state was reached after 102 days. For *M. nasuta*, Boese et al. (1997) approximated steady state for DDT in the range of 86–217 days while Lee et al. (1994) reported a range of 60 to ≥90 days. The fraction of steady state for *M. nasuta* after 28 days fell well short of 80% for all DDTs,

ranging from 50 to 63%. This finding was corroborated by values of 10–60% summarized in ASTM (2000). Time to steady state for both organisms is summarized in Figure 8.

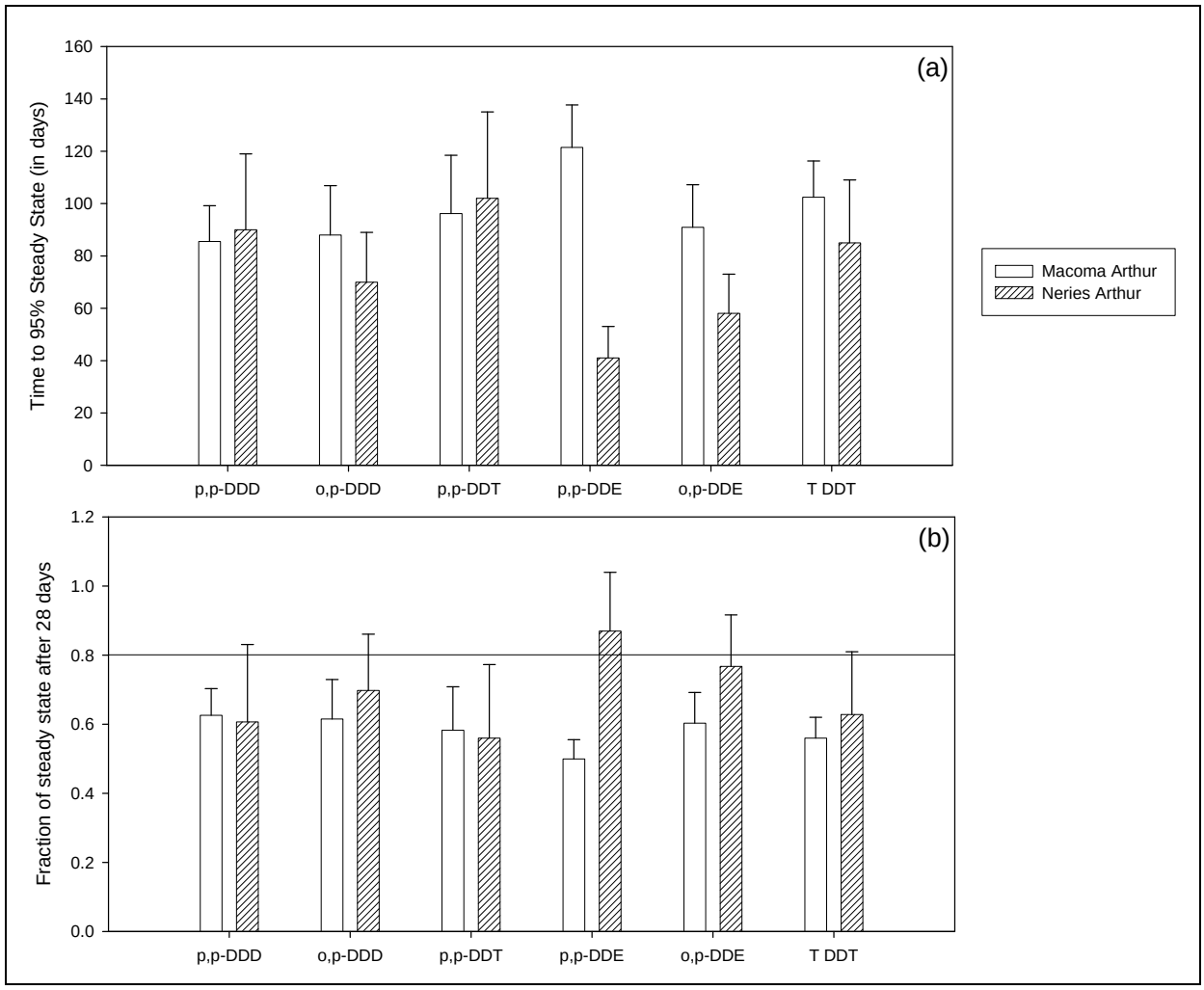

Figure 8. Time to 95% steady state (TSS) (a) and fraction of steady state ($f_{ss\text{-}28d}$) (b) derived for DDTs in *Macoma nasuta* and *Nereis virens* in this study. The solid line in panel (b) indicates 80% of steady state.

Since most DDTs, DDEs, and DDDs did not reach steady state within 28 days and do not offer a wide range in log K_{ow} values (6.22–6.95), the fraction of steady state (f_{ss}) was below 0.8 for both organisms and no clear relationship was observable between log K_{ow} and f_{ss}.

Steady-state BSAFs were consistently higher than 28-d BSAFs, and were similar among analytes with the exception of the substantially lower BSAF for o,p-DDE for *N. virens* and p,p'-DDT for *M. nasuta* (Figure 9). The steady-state BSAFs determined in this study fell within the range of 0.118 to 0.479 for p,p-DDTs reported for *N. virens* (Metcalf and Eddy, Inc. 1995).

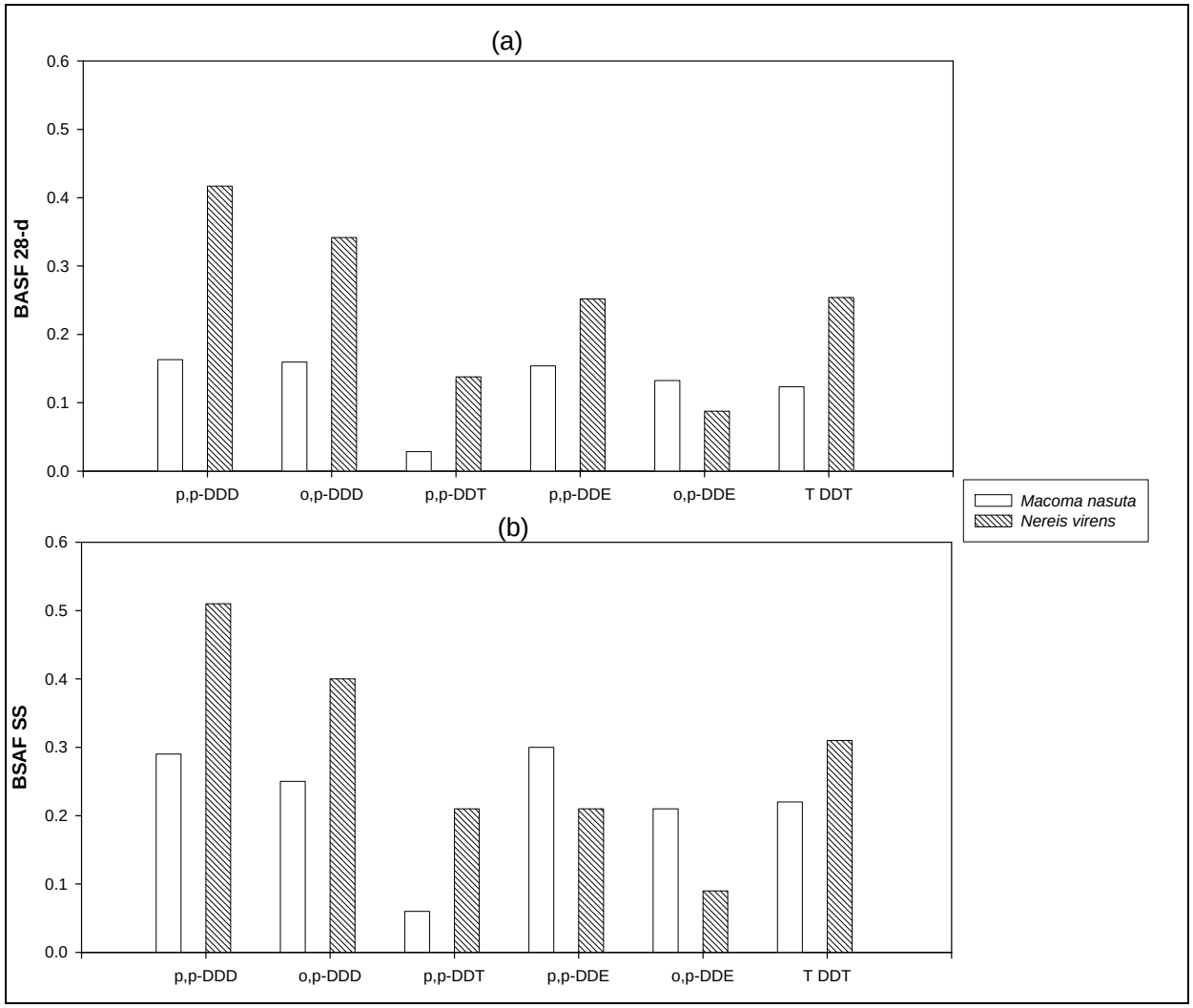

Figure 9. Mean instantaneous 28-d biota to sediment accumulation factors (BSAF) (a) and kinetically modeled at steady state BSAF at steady state (BSAF SS) (b) biota to sediment accumulation factors for *Nereis virens* and *Macoma nasuta* exposed to the Arthur Kill sediment.

BASF values for *M. nasuta* exposed to field-contaminated sediment reported by Ferraro et al. (1990) and Boese et al. (1997) were typically higher than values determined for the Arthur Kill sediment. Boese et al. (1997) reported that the *M. nasuta* BSAF for p,p-DDT (0.09) was lower than DDDs and DDEs (0.72 - 1.67), a finding corroborated by this study.

Polychlorinated biphenyls (PCBs)

PCB sediment chemistry (Table A2), kinetics information (Tables B2 and C2), and uptake curves (Figures D2 and E2) are summarized in detail in the appendices.

The uptake kinetics of PCB congeners were similar in both sediments for *N. virens* but were substantially different between sediments for *M. nasuta* (Figure 10). Tissue residue in *N. virens* in both sediment exposures and *M. nasuta* in the Newark Bay exposure reached at least 80% of steady state for all congeners within 28 days. However, *M. nasuta* exposed to Arthur Kill sediment required longer than 28 days to reach 80% of steady state for 10 of the 12 congeners for which significant uptake curves were obtained.

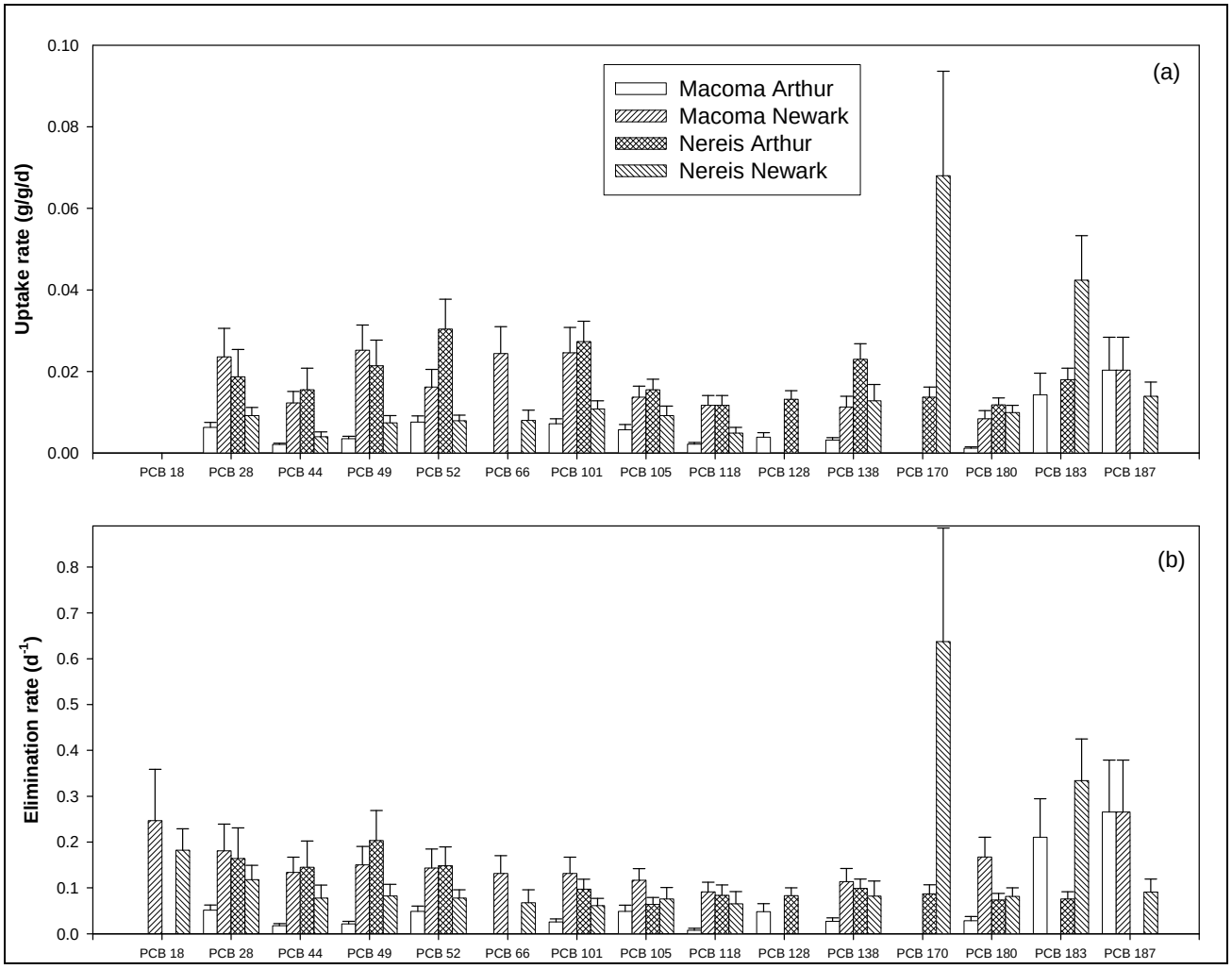

Figure 10. Uptake (a) and elimination rates (b) for select PCB congeners derived in this study for *Macoma nasuta* and *Nereis virens*. Missing congeners were no detected in tissues at levels sufficient for modeling.

For *N. virens*, the uptake rates for PCBs were higher in the Arthur Kill sediment for all congeners except 183, suggesting lower bioavailability of PCBs in the Newark Bay sediment. This is the opposite of the expected bioavailability based on the TOC for Arthur Kill (2.9%) and Newark Bay sediments (2.2%). For *M. nasuta*, however, the uptake rates for PCBs were

consistently higher in the Newark Bay sediment, suggesting lower PCB bioavailability in the Arthur Kill sediment, as would be predicted by TOC and black carbon content (Table 2).

Uptake rates for *M. nasuta* determined in this study are compared to rates reported by Boese et al. (1997) for spiked compounds (Figure 11). Uptake rates for all compounds were a magnitude higher in spiked sediment compared to field-contaminated sediment. It has been documented by others that chemicals spiked into sediments are more bioavailable (Kukkonen and Landrum 1998). A similar magnitude of difference was reported by Boese et al. (1997) for PCB 153. Studies specifically reporting uptake rates for PCBs in *N. virens* in sediment exposures were not found in the available literature.

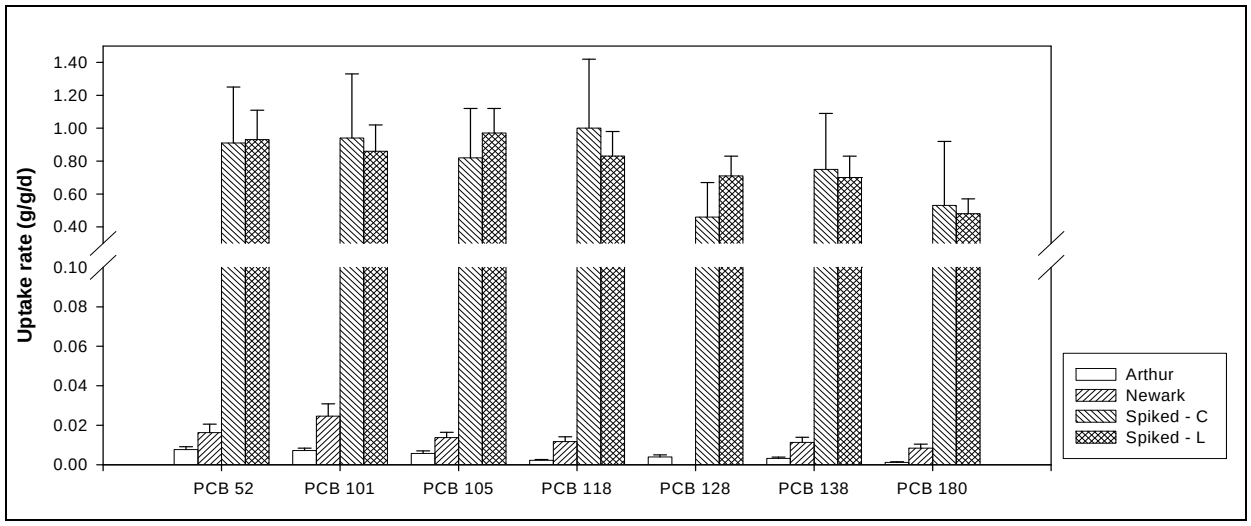

Figure 11. Uptake rates for PCB analytes in *Macoma nasuta* for this study and from spiked sediments in Boese et al. (1997). Boese et al. (1997) measured rates by two methods: (1) by estimates derived from curve fitting (Spiked C), as in this study, and (2) by direct measurement of linear uptake and elimination (Spiked L).

The rates of elimination (Figure 10b) estimated by modeling the uptake curve were similar in both sediments for *N. virens*. For *M. nasuta*, however, elimination was apparently more efficient in the Newark Bay sediment exposure. Boese et al. (1997) determined elimination rates by two methods; (1) modeling the uptake curve and indirectly calculating the rate of elimination (as in the current study); and (2) directly measuring depuration rates by transferring exposed organisms to uncontaminated sediment. Both of these methods determined similar elimination rates to those determined in the Arthur Kill sediment exposure from the current study. Since elimination of bioaccumulated compounds is expected to occur at a constant rate irrespective of uptake source, the actual elimination rates in

the Newark Bay sediment were likely similar to those determined in the Arthur Kill sediment in this study and in spiked sediments in the study by Boese et al. (1997) (Figure 12). The exceptionally high apparent rates of elimination from the Newark Bay exposure may have resulted from a gradual decrease in uptake rate over time (resulting from a change in the bioavailable chemical fraction) causing faster apparent approach to steady state than in the Arthur Kill sediment. The model used in this study (Equation 1) assumes a constant uptake rate and depends on this to accurately extrapolate elimination. Goerke and Ernst (1977) determined elimination rates of PCB congeners 4, 31, and 100 in water only following dosing animals via feeding with contaminated food. The elimination rates were 0.03, 0.057, and 0.011 d^{-1} for PCBs 4, 31, and 100, respectively. Those rates were substantially lower than those determined in the uptake experiment in this study for PCBs 28 (0.118 and 0.164 d^{-1}) and 101 (0.061 and 0.097 d^{-1}). The higher rates of elimination observed in this study are likely due to faster elimination of hydrophobic compounds in sediment than in water only for benthic invertebrates, as demonstrated for PAHs (Lotufo and Landrum 2002) and chlorinated compounds (Lydy et al. 1992). Previous reports of the elimination rates of PCBs in *N. virens* in the presence of sediment were not found in the available literature. Studies directly measuring the elimination rate of PCBs in *N. virens* following exposure to PCBs are needed.

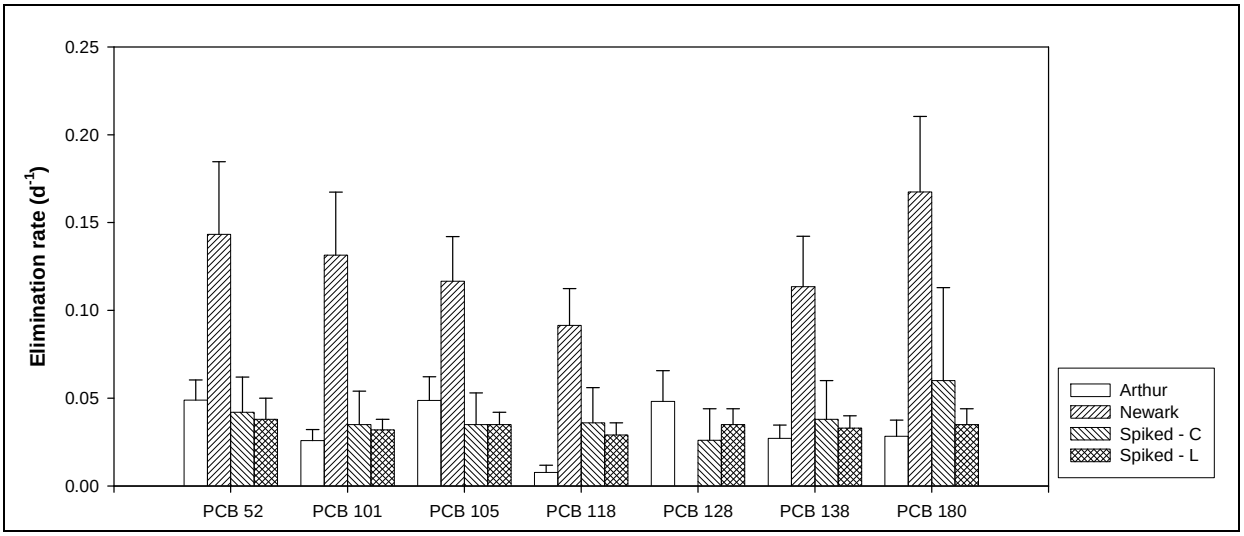

Figure 12. Elimination rates for PCB analytes in *Macoma nasuta* for this study and from spiked sediments in Boese et al. (1997). Boese measured rates by two methods: (1) by estimates derived from curve fitting (Spiked- C), as in this study, and (2) by direct measurement of linear uptake and elimination (Spiked - L). The Boese data corroborates the Arthur Kill data set from this study.

For *N. virens*, there was reasonable agreement between congeners for kinetics parameters and thus TSS (5 to 49 days) and in both sediments, with the exceptions of congeners 170 and 183, for which steady state was achieved considerably faster in the Newark Bay exposure (Figure 13) due to high estimated elimination rates (Figure 10). Rubinstein et al. (1983) noted that time to approach steady state for PCBs in *N. virens* varied between 20 and 40 days in four different New York Harbor sediments. In the study by Rubinstein et al. (1983), apparent elimination rates and time to steady state varied considerably among sediments.

As a result of differences in elimination rate estimates, considerable differences in the model estimations of TSS between the Arthur Kill (range 40 to 140 days, median TSS = 62 days) and Newark Bay (range 11 to 33 days, median TSS = 22 days) were determined for *M. nasuta* (Figure 13). The median 28-d fraction of steady state was considerably lower for the Arthur Kill exposure (f_{ss} = 0.65) relative to the Newark Bay exposure (f_{ss} = 0.98). Thus, based on model projections from the data, the adequacy of the standard 28-d exposure period for steady-state bioaccumulation of PCBs in *M. nasuta* appear to be sediment-dependent, as suggested by Rubinstein et al. (1983). However, the range (63 to 267 days) of TSS reported by Boese et al. (1997) for *M. nasuta* exposed to spiked PCBs corresponds more closely to the values obtained in the Arthur Kill exposure. Thus, it is reasonable to conclude that the kinetics information obtained from the Arthur Kill exposure could be used as a more conservative estimation of steady state for a wide range of sediments from the New York Harbor area. The high TSS reported for PCB 118 (390 days) in the Arthur Kill exposure should be interpreted with caution provided the 119-d tissue residue was almost twofold greater than the apparently stable 28- through 90-d time tissue residue (Appendix D2).

Pruell et al. (1990, 1993) reported relatively slow acquisition of steady state for *N. virens* but fast uptake for *M. nasuta* exposed to PCBs based on statistical comparison between time points (Figure 14). The average mass of the *N. virens* (3.97 ± 1.35 g) and *M. nasuta* (1.87 ± 0.37 g), reported in Pruell et al. (1993), was similar to the current study (see methods section), suggesting similar kinetics. These findings contrast with the Arthur Kill data set in this study, where uptake and elimination rates were much slower in *M. nasuta* relative to *N. virens*. Four important differences in methodology existed in the Pruell et al. study:

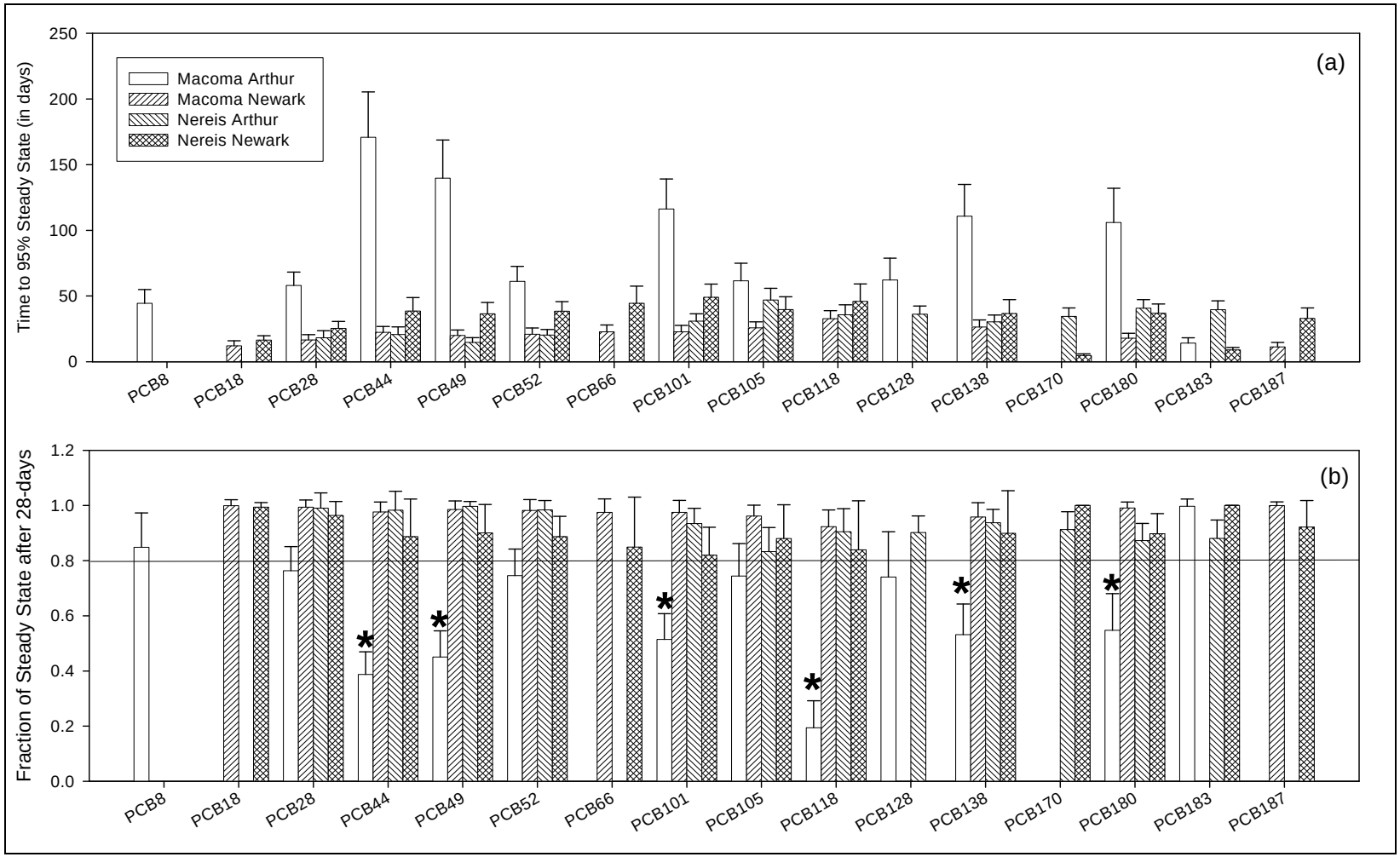

Figure 13. Time to 95% steady state (TSS) (a) and fraction of steady state ($f_{ss\text{-}28d}$) (b) derived for PCBs in *Macoma nasuta* and *Nereis virens* in this study. The solid line in panel b indicates 80% of steady state. PCB 118 (TSS = 390 days) was excluded for Macoma Arthur Kill due to a large jump in the last timepoint. Asterisks highlight the congeners that did not reach at least 80% of steady state after 28 days.

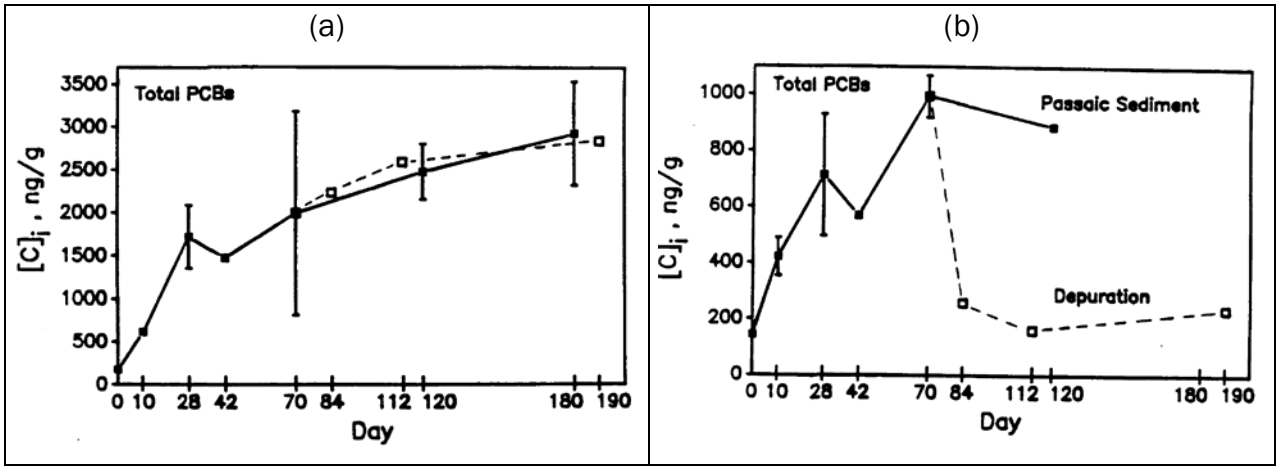

Figure 14. Uptake curves for *Nereis virens* (a) and *Macoma nasuta* (b) as reported by Pruell et al. (1990).

1. *Pruell conducted the exposures at 18–22 ℃.* While this temperature range is comparable to the *N. virens* exposure in the current study (20 °C), it is higher than the *M. nasuta* exposure conducted in this study (15 °C) and higher than guidance in the Inland Testing Manual (USEPA/USACE 1998) of 12–16 °C. Conducting bioassays at higher temperatures may increase organism activity, metabolism, and thus uptake and elimination kinetics leading to faster acquisition of steady state. Consequently, the *M. nasuta* kinetics obtained in the current study are likely to better represent the rates of bioaccumulation used in dredged material evaluations.
2. *No renewal of test sediment was reported throughout the 120- to 180-day exposure periods*. Sediment additions and renewals during long-term bioaccumulation exposures are strongly recommended, as test organisms may locally deplete sediments of contaminants (Lee et al. 1993 and references within, Boese et al. 1995). Local depletion of PCBs in the sediment is a situation that may be especially problematic for the more sedentary *M. nasuta* (ASTM 2000). Theoretically, any change in chemical concentration or bioavailability may result in a premature plateau or even dip in the uptake.
3. *A 24-hr water-only purging period was conducted to address removal of digested sediment remaining in the guts of test organisms following exposure*. This method may lead to incomplete gut purging relative to other methods (gut dissection, transfer into clean sediments). This may be problematic for *M. nasuta* since the clams may not be able to fully clear their guts without assistance from incoming sediment.
4. *Steady state was not kinetically determined (by curve fitting).* Examination of the curves without the kinetic approach may present subjectivity. While Lee et al. (1993) reported slow chemical depuration from *M. nasuta*

(4 and 12% after 24 and 48 hr, respectively), the depuration by *M. nasuta* was reported (Pruell et al. 1990) to be rapid and replication may have been limited due to unexpected mortality. Additionally, the TOC of the Passaic River sediment used was considerably higher (5.7%) than either of the sediments examined in this study (Table 2), which may have reduced bioavailability.

Rubinstein et al. (1983) found *N. virens* to reach steady state much more rapidly (30–40 days) and corroborates the data set in the current study. An additional study by Drouillard et al. (2008) has confirmed that *N. virens* achieves steady state within 28 days for a wide range of PCB congeners accumulated from sediment from the Hudson River. The current results suggest that 28-d exposure is adequate for all congeners (Figure 15) to reach steady-state tissue residues in *N. virens* and thus a correction factor is not necessary. For *M. nasuta*, it is recommended that the estimates from the Arthur Kill exposure (corroborated by Boese et al. 1997 and ASTM 2000) be given precedence for more conservative risk calculations; therefore, PCBs in *M. nasuta* may require greater than 28 days to reach steady-state tissue residues and correction factors are necessary (Table 4).

All PCB congeners, regardless of K_{ow} (range: 5.24–7.36), reached at least 80% of steady state for *N. virens* in both test sediments (Figure 15). While all congeners also reached at least 80% steady state in *M. nasuta* in the Newark Bay exposure, congeners with K_{ow} values greater than 5.5 generally did not reach 80% steady state in exposure to the Arthur Kill sediment.

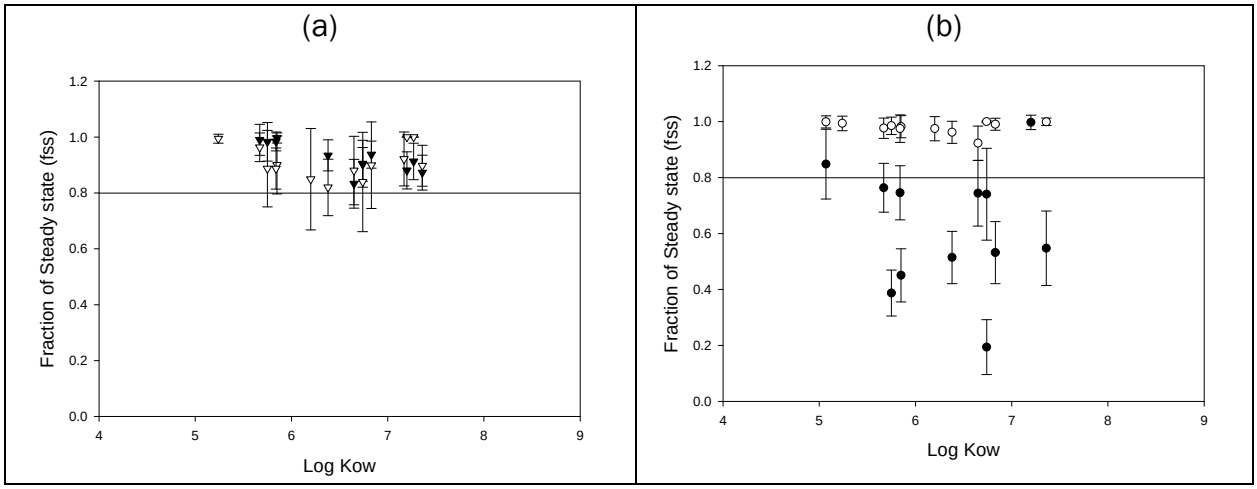

Figure 15. Log K_{ow} versus 28-d fraction of steady state (f_{ss}) for (a) *Nereis virens* (triangles) and (b) *Macoma nasuta* (circles) exposed in the Arthur Kill (filled points) and Newark Bay (open points) sediment. Error bars indicate standard error. The horizontal line indicates 80% of steady state.

For *N. virens*, the 28-d and steady-state BSAFs were similar among congeners and between the Arthur Kill and Newark Bay sediment exposures (Figure 16). The BSAFs obtained in this study were lower overall compared to previously reported values (0.19–1.41) (Pruell et al. 1993).

For *M. nasuta*, the 28-d and steady-state BSAFs were similar among congeners. However, 28-d BSAFs were consistently higher for the Arthur Kill sediment and steady-state BSAFs were higher in the Arthur Kill sediment for all congeners except PCB 128. Literature values for *M. nasuta* BSAFs in the ERDC BSAF database varied greatly, generally ranging from 0.06 to 4.79, with outliers as high as 19.2 (Ferraro et al. 1990, 1991; Brannon et al. 1993; Pruell et al. 1993; Boese et al. 1995, 1996). Overall, the BSAFs obtained in this study for *M. nasuta* were lower compared to previously reported values.

Based on kinetics data from this study and previous reports, the 28-d bioaccumulation test duration is adequate for PCB concentrations to reach 80% of steady state in *N. virens* tissue (Figure 15) but too short for *M. nasuta* tissues to approximate steady state based on the more conservative estimate derived from the Arthur Kill sediment and Boese et al. (1997).

Dioxins and furans

Dioxins/furans sediment chemistry (Table A3), kinetics information (Tables B3 and C3), and uptake curves (Figures D3 and E3) are summarized in the appendices.

The majority of dioxin and furan compounds (14 out of 18 compounds) reached at least 80% of steady state in *N. virens* but a much smaller percentage of compounds reached at least 80% of steady state in *M. nasuta* (7 out of 18 compounds) after 28 days of exposure in both test sediments. Thus, standard 28-d bioaccumulation test duration appeared adequate for *N. virens* (i.e., no correction factors needed with the exception of TCDD) but longer exposure duration is required for *M. nasuta* for steady-state bioaccumulation determination of dioxins and furans (i.e., correction factors are needed).

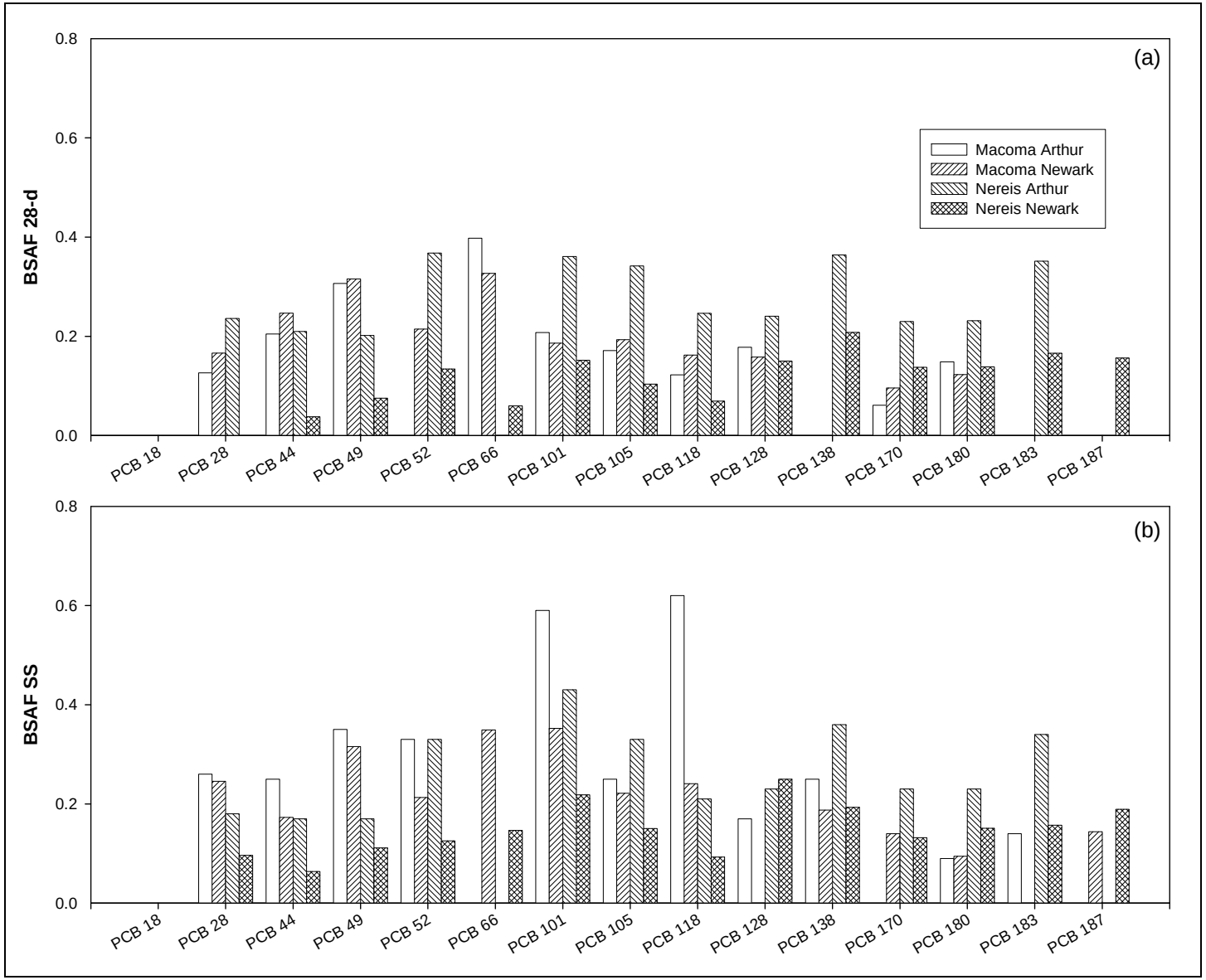

Figure 16. Mean instantaneous 28-d biota to sediment accumulation factors (BSAF) (a) and kinetically modeled at steady state BSAF at steady state (BSAF SS) (b) biota to sediment accumulation factors for *Nereis virens* and *Macoma nasuta*.

Bioaccumulation was evaluated for 18 dioxin and furan compounds and the sum concentration of classes of compounds detected in the sediment samples (Table A3).

For *N. virens*, uptake and elimination rate constants were determined for 17 and 12 dioxins and furans for the Arthur Kill and Newark Bay sediment exposures, respectively (Table B3). Bioaccumulation patterns that did not fit the model (Equation 1) prevented determination of uptake kinetics rates for six dioxins and furans in the Arthur Kill sediment and 11 dioxins and furans in the Newark Bay sediment (Table B3). The uptake rates were higher in the Newark Bay sediment exposure for most dioxins and furans. This finding contrasts with the PCB trends in *N. virens* but is consistent with sediment TOC levels. Relatively high uptake rates were determined for 2,3,7,8-TCDF, Total TCDF, and Total PeCDF in the Newark Bay sediment.

For *M. nasuta*, the temporal pattern of bioaccumulation was determined for 25 and 17 dioxins and furans for the Arthur Kill and Newark Bay sediments (Tables C3 and C7). Bioaccumulation patterns that did not fit the model (Equation 1) prevented determination of uptake kinetics rates for two dioxins and furans in the Arthur Kill sediment and one compound in the Newark Bay sediment. The uptake rates were higher in the Newark Bay sediment for most dioxins and furans that yielded kinetic curves for both sediments (Figure 17, Table E3) indicating lower bioavailability in the Arthur Kill sediment. This finding is consistent with the lower bioavailability of PCBs in the Arthur Kill sediment. Relatively high uptake rates were determined for Total TCDD and Total TCDF in the Newark Bay sediment. Reporting of uptake of dioxins rates from sediments by *M. nasuta* were not found in the available literature.

The rates of elimination estimated by modeling the uptake curve were relatively similar in both sediments for most compounds or sum of compounds for *N. virens* and *M. nasuta* (Figure 17). Reports of rates of uptake and elimination of dioxins and furans by *N. virens* and *M. nasuta* were not found in the available literature.

For *N. virens*, most (80%) dioxins and furans reached 80% of steady-state residue tissue after 28-d (Table 4, Figure 18). However, some analytes (e.g., 2,3,7,8-TCDD, 1,2,3,6,7,8-HxCDD, 2,3,4,7,8-PeCDF) required longer periods of time (Figure 18). The analyte that had the lowest fraction of

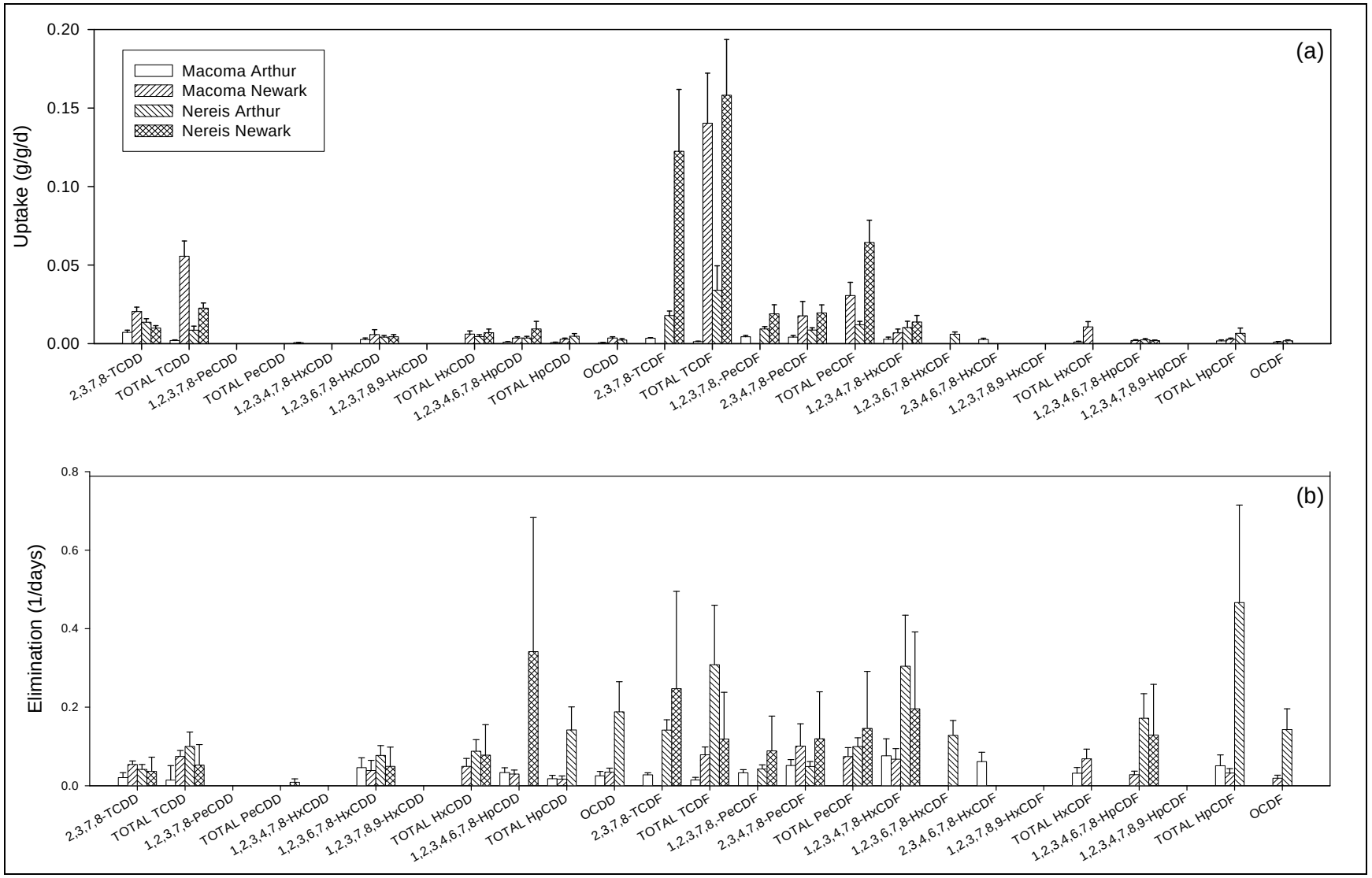

Figure 17. Uptake (a) and elimination rates (b) for dioxins and furans analytes derived in this study for *Macoma nasuta* and *Nereis virens*.

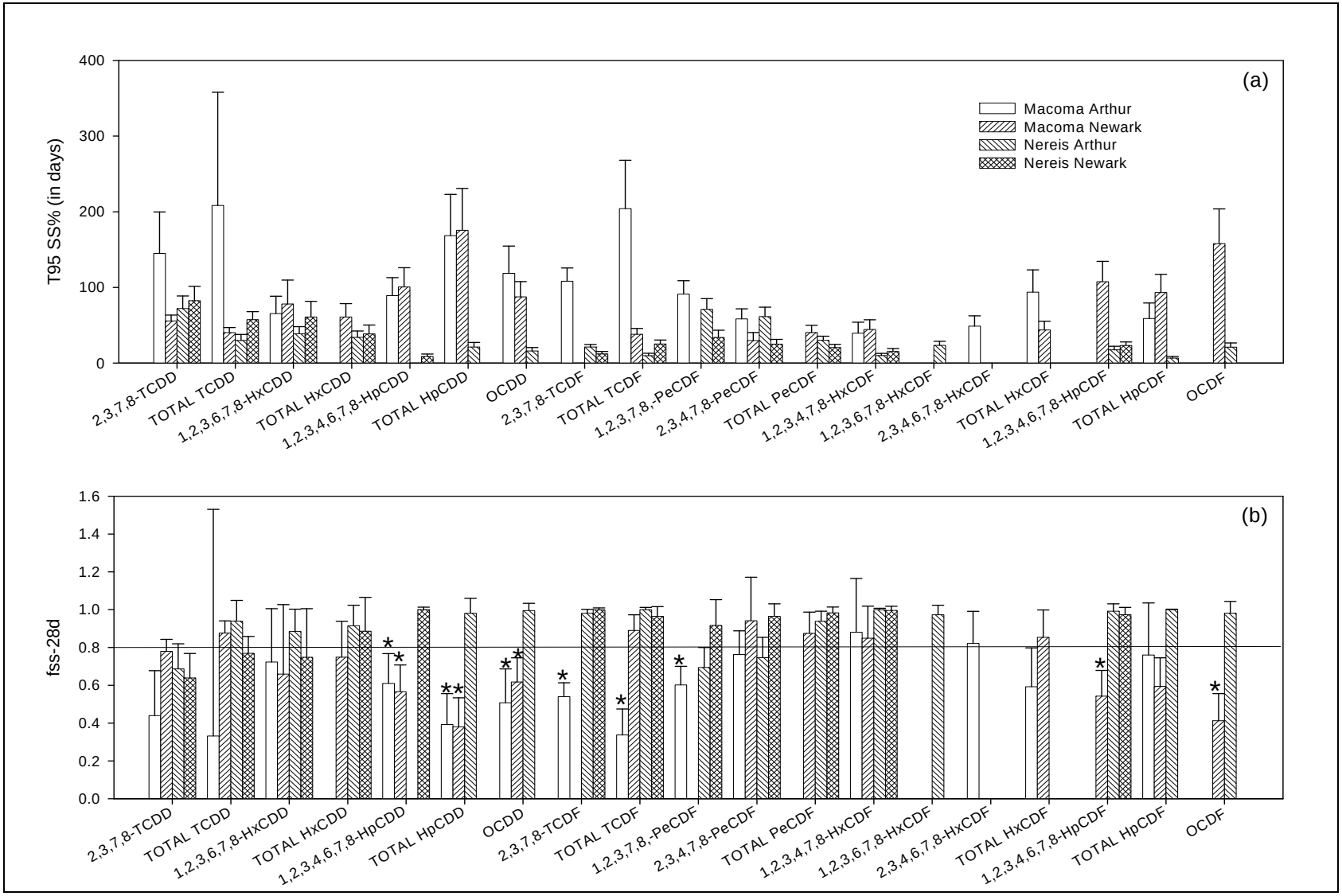

Figure 18. Time to 95% steady state (TSS) (a) and fraction of steady state ($f_{ss\text{-}28d}$) (b) derived for dioxins and furans in *Macoma nasuta* and *Nereis virens* in this study. The solid line in panel b indicates 80% of steady state. Asterisks highlight the congeners that did not reach at least 80% of steady state after 28 days.

steady state at day 28 was 2,3,7,8-TCDD (64 – 67%), for which ASTM (2000) reported 22% of steady state obtained after 28 days of exposure. Overall, the TSS ranged from 6 to 82 days, with a median value of 23 days. Good agreement in kinetics parameters for specific dioxins and furans between the Arthur Kill and Newark Bay exposures was obtained, with the exception of 1,2,3,7,8-PeCDF and 2,3,4,7,8-PeCDF where the time to steady state and 28-day fraction of steady state for the Arthur Kill exposure were notably higher and lower, respectively. The temporal pattern of bioaccumulation of 2,3,7,8-TCDD from Passaic River (NJ) by *N. virens* reported in Pruell et al. (1990) (Figure 19) suggested a longer time for steady state than those determined in this study for the Newark Bay and Arthur Kill sediments (Tables B3 and C3). For 2,3,7,8-TCDF, however, the temporal pattern reported in Pruell et al. (1990) suggests a fast time to steady state as determined in this study.

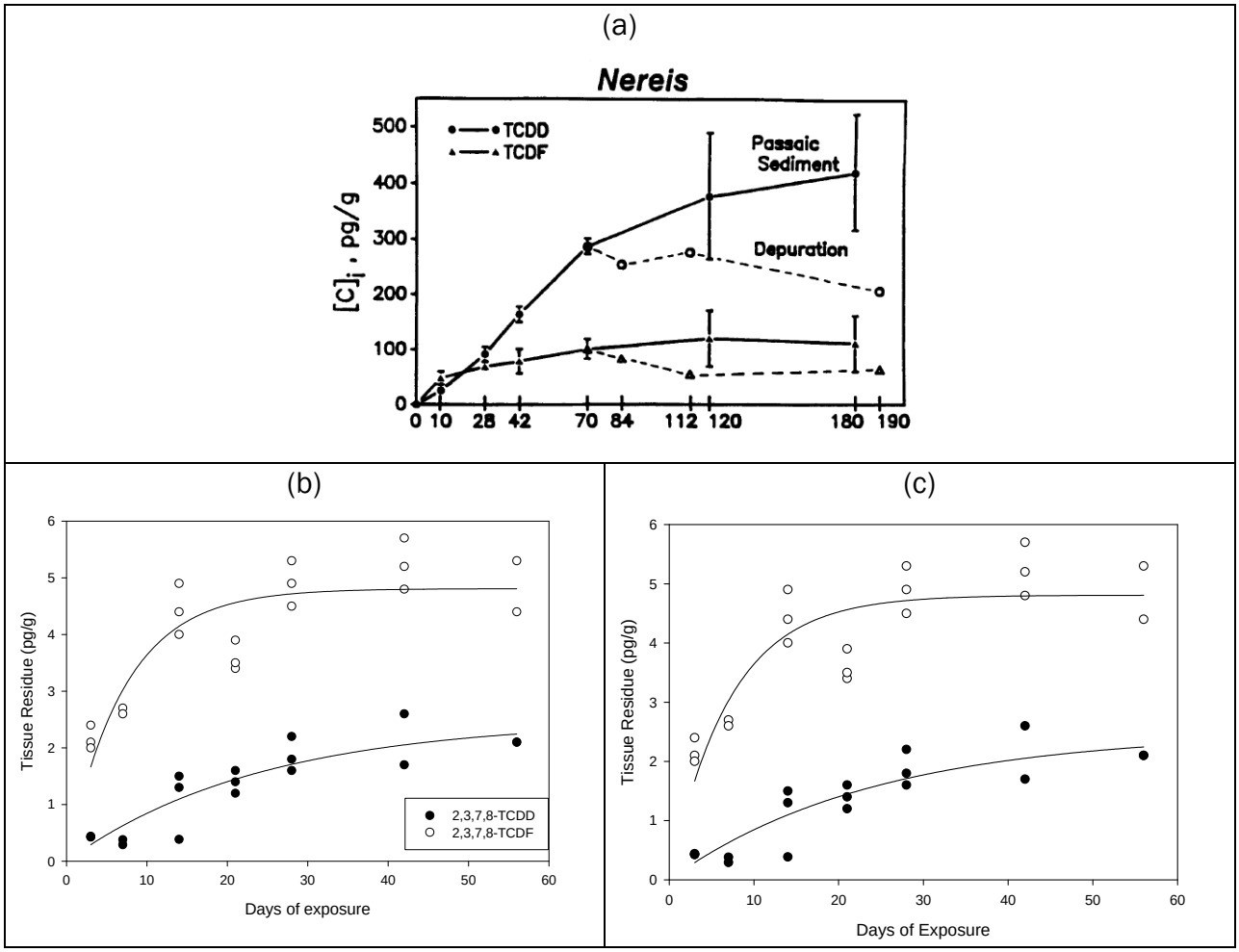

Figure 19. Uptake and elimination kinetics for *Nereis virens* exposed to TCDD and TCDF in (a) Passaic River sediment (Pruell et al. 1990), (b) Arthur Kill sediment (this study), and (c) Newark Bay sediment (this study).

Similar to the results from the *M. nasuta* exposure to PCBs, the modeled time to steady state for dioxins and furans was longer than 28 days. The median TSS in the Arthur Kill sediment was 93 days and fraction of steady state at day 28 was 0.59 while for the Newark Bay sediment the median $TSS_{95\%}$ was 53 days and the fraction of steady state at day 28 was 0.75. There was a smaller difference between kinetic parameters for dioxins and furans for the two sediments tested as compared to the wide differences observed for PCBs using the same sediments. Using a visual inspection of *M. nasuta* time-dependent tissue residue curves, ASTM (2000) reported fractions of steady state at day 28 of 80 and 100% for TCDD and TCDF, respectively. These values correspond more closely with the Newark Bay sediment exposure of this study. The temporal pattern of bioaccumulation of 2,3,7,8-TCDD from Passaic River (NJ) by *M. nasuta* reported in Pruell et al. (1990) (Figure 20) suggest a shorter time for steady state than those determined in this study for the Newark Bay and Arthur Kill sediments (Tables B3 and C3). For 2,3,7,8-TCDF, the temporal pattern reported in Pruell et al. (1990) suggest a much shorter time to steady state than determined in this study for the Arthur Kill sediment, whereas no increase in tissue residue was apparent for that compound in the Newark Bay sediment in this study (Appendix E). See the PCB discussion for description of the differences that existed between these two studies.

Log K_{ow} values (6.46 – 8.75) are on the high end for dioxins and furans. No obvious pattern was observed for *N. virens*, although there were compounds ($K_{ow} > 7$) in both sediment exposures that did not reach steady-state tissue residues after 28 days (Figure 21). For *M. nasuta*, however, all compounds with log K_{ow} values that exceeded 8.0 did not reach 80% of steady state after 28 days.

For *N. virens*, the 28-d measured BSAF were typically lower than steady-state BSAFs, which ranged widely from 0.02 to 1.65 (Figure 22). BSAF values were generally comparable for the same analytes between the two sediment exposures, with discrepancies for total 2,3,7,8-TCDD, 2,3,7,8-TCDF, total TCDF, and total PeCDF. BSAF values previously reported for TCDD and TCDF ranged from 0.11 to 0.50 (Pruell et al. 1993; Schrock et al. 1997) and were overall similar to the steady state BSAFs obtained in this study.

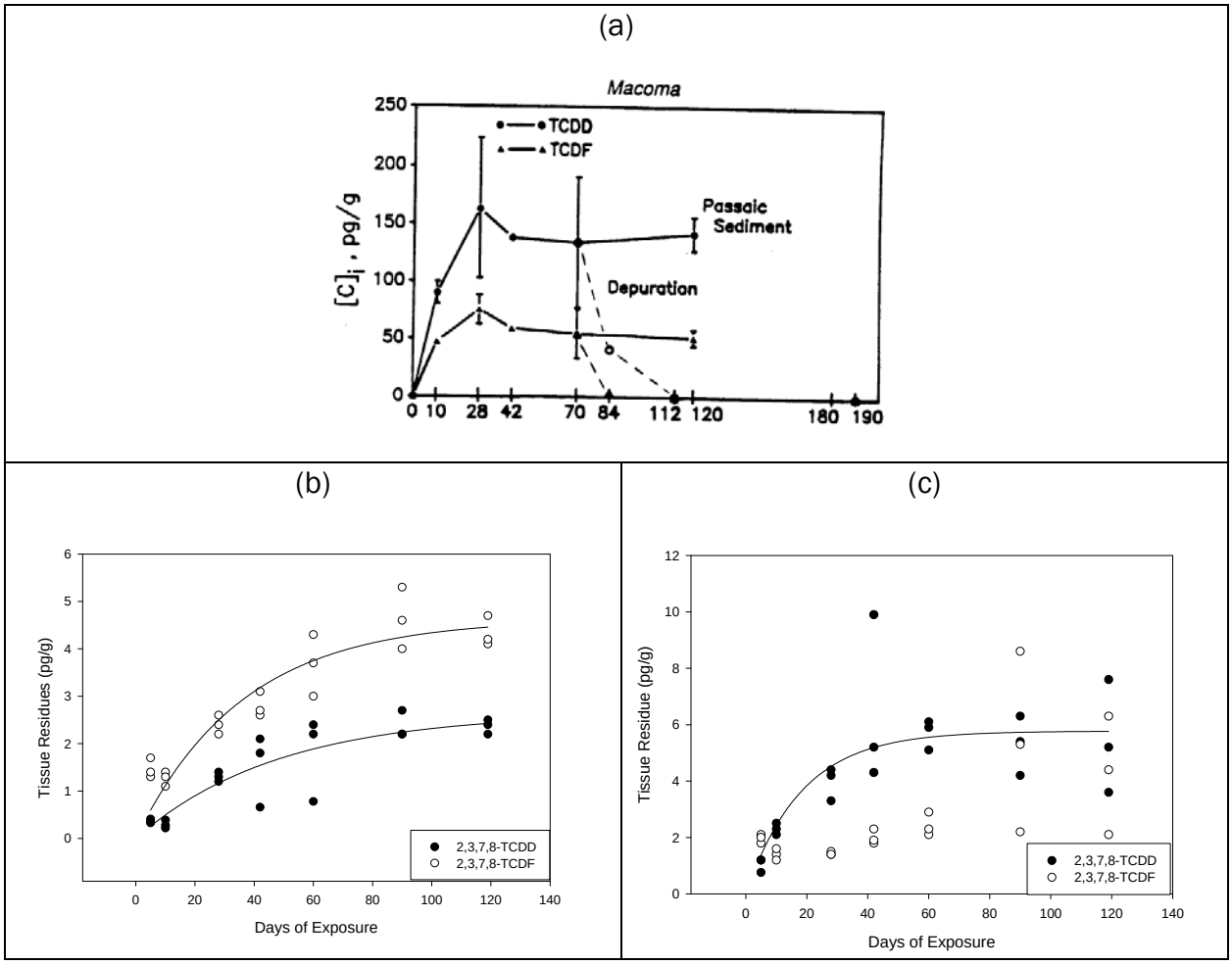

Figure 20. Uptake and elimination kinetics for *Macoma nasuta* exposed to TCDD and TCDF in (a) Passaic River sediment (Pruell et al. 1990), (b) Arthur Kill sediment (this study), and (c) Newark Bay sediment (this study).

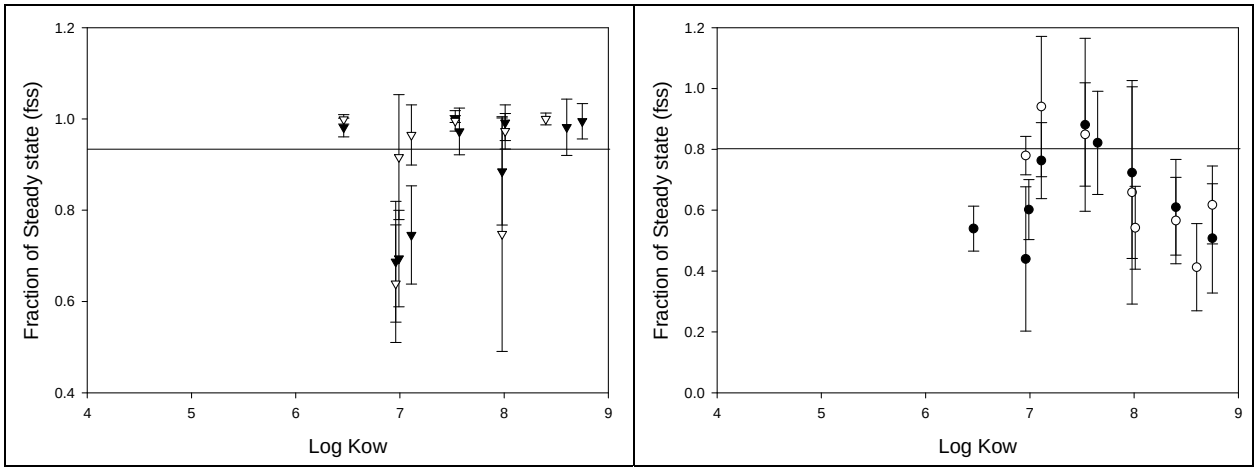

Figure 21. Log K_{ow} versus 28-d fraction of steady state (f_{ss}) for (a) *Nereis virens* (triangles) and (b) *Macoma nasuta* (circles) exposed in the Arthur Kill (filled points) and Newark Bay (open points) sediment. Error bars indicate standard error. The horizontal line indicates 80% of steady state.

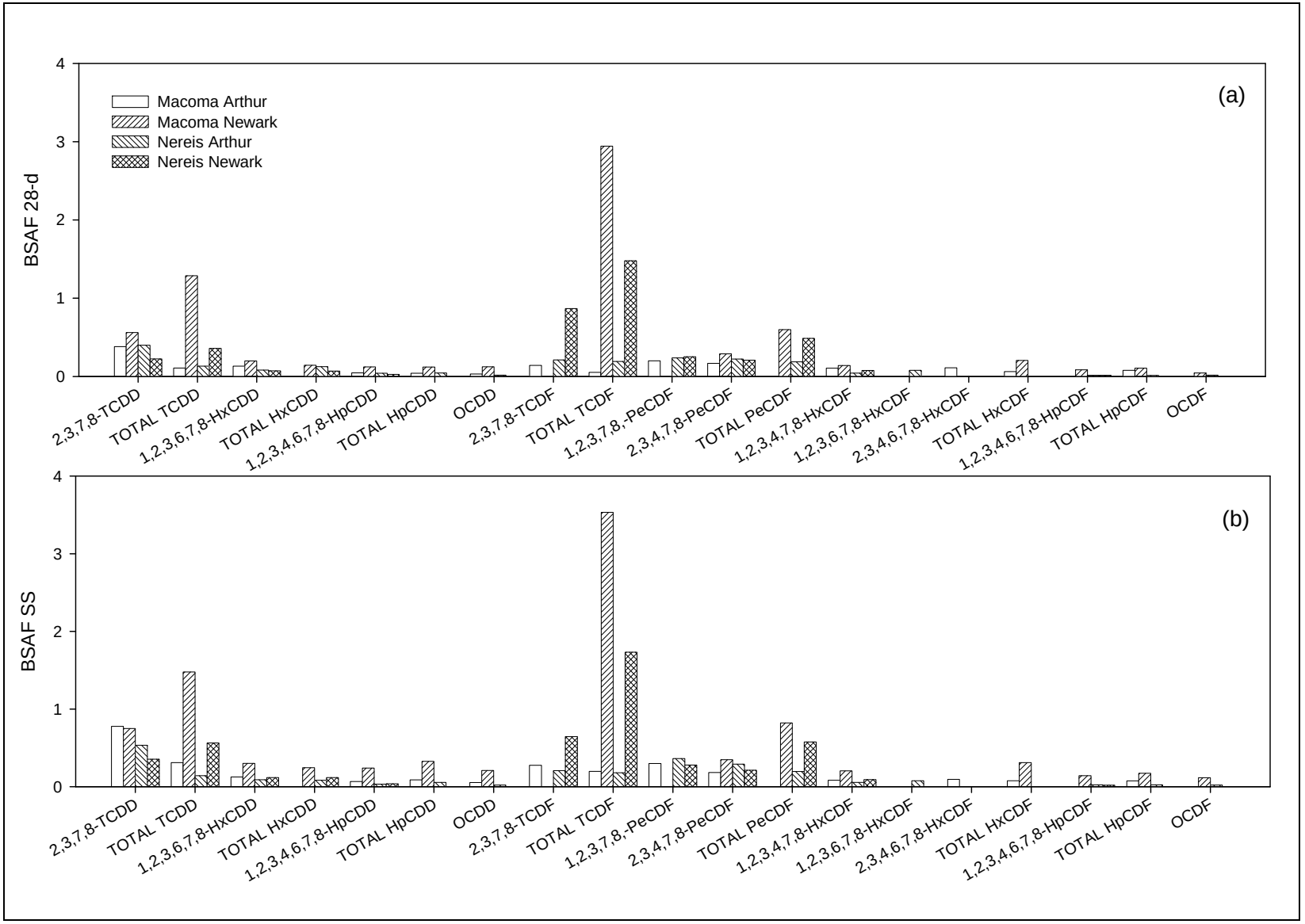

Figure 22. Mean instantaneous 28-d biota to sediment accumulation factors (BSAF) (a) and kinetically modeled at steady-state BSAF at steady state (BSAF SS) (b) biota to sediment accumulation factors for *Nereis virens* and *Macoma nasuta*.

For *M. nasuta*, the 28-d measured BSAF values were typically lower than steady-state BSAFs, which ranged widely from 0.05 to 3.36 (Figure 22). BSAF values were generally comparable for the same analytes between the two sediment exposures, with most notable discrepancies found for 2,3,7,8-TCDD and 1,2,3,4,6,7,8-HpCDD. The BSAF values found in the literature for 2,3,7,8-TCDD and 2,3,7,8-TCDF were 0.90 and 0.70, respectively (Pruell et al. 1993) and were comparable to the steady-state values of 0.26 to 1.03 determined in his study.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAH sediment chemistry (Table A4), kinetics information (Tables B4 and C4), and uptake curves (Figures D4 and E4) are summarized in the appendices.

Bioaccumulation of PAHs was detectable for only three compounds in *N. virens* and seven compounds in *M. nasuta*. Based on the limited information derived in this study and information obtained from the available literature, the standard 28-d test duration is adequate to obtain steady-state tissue residues in *N. virens*. The same is true for *M. nasuta* based on results from Newark Bay sediment exposures. The higher time to steady state determined for Arthur Kill sediments may suggest that changes in bioavailability over time lead to increased body residues after the 28-d standard exposure period.

Among the PAHs with measurable sediment concentrations (Table 2), only fluoranthene, pyrene, and chrysene were detected in *N. virens* tissues. Because steady state was reached before the first sampling time point (t = 3 days), uptake rates could not be determined for chrysene and fluoranthene in the Newark Bay sediment and chrysene in the Arthur Kill sediment. Rapid acquisition of steady state in *N. virens* is supported by Ciarelli et al. (2000) for flouranthene (≤ 5 days). The uptake rates determined for fluoranthene and pyrene were very similar (Table B4; Figure 23). Lack of detectable bioaccumulation of most PAHs in *N. virens* present in the sediment may be due to the highly efficient metabolism of PAHs by this polychaete worm (McElroy 1990; Driscoll and McElroy 1996; Rust et al. 2004; Jorgensen et al. 2005). Unless the project goal is to assess uptake in organisms that are efficient metabolizers of PAHs, this invertebrate species may be inappropriate to assess the bioaccumulation potential of PAHs in dredged material (Driscoll and McElroy 1996).

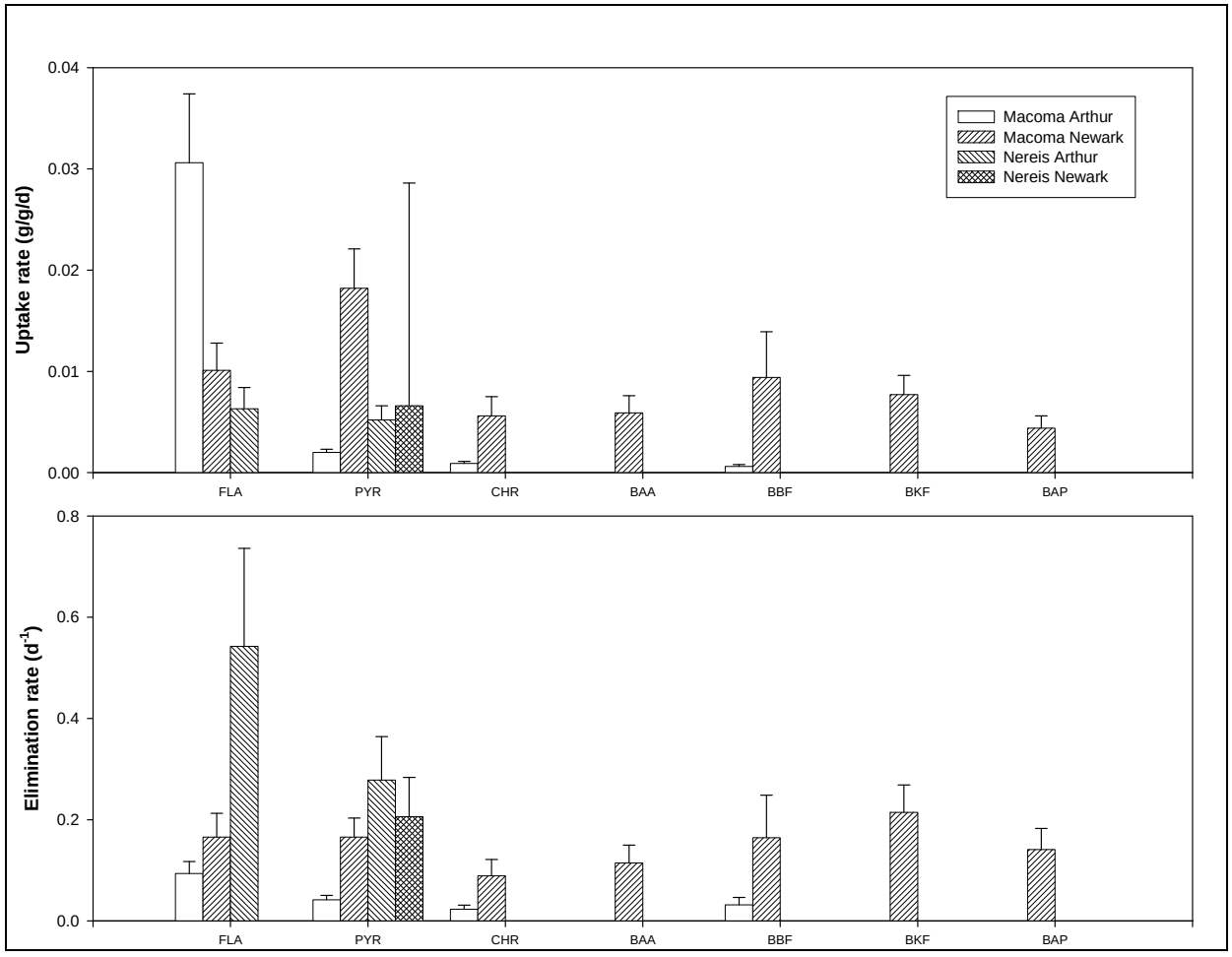

Figure 23. Uptake (a) and elimination rates (b) for PAH analytes derived in this study for *Macoma nasuta* and *Nereis virens*.

Uptake rates of PAHs in *M. nasuta* were determined for the seven PAHs detected in the tissue of exposed clams (Table C4; Figure 23). Those rates were similar, ranging from 0.0056 to 0.0182 g/g/d. For the Arthur Kill sediment, however, lack of increases in tissue residue from days 7 to 120 precluded determination of uptake rates for benzo[a]anthracene, benzo[a]pyrene, and benzo[k]fluoranthene (Figure 23). The uptake rates of fluoranthene, pyrene, chrysene, and BBF ranged widely from 0.0006 to 0.0306 g/g/d. Except for fluoranthene, uptake rates were substantially slower in the Arthur Kill sediment compared to the Newark Bay sediment, similar to rates determined for PCBs. Information on the uptake kinetics of PAHs from sediment by *M. nasuta* was not found in the available literature.

For *N. virens* , the rates of elimination estimated by modeling the uptake curve (Table D4) were very high for fluoranthene and pyrene (Table B4; Figure 23). The elimination rate for fluoranthene determined for the Arthur Kill sediment exposure (0.54 d^{-1}) was very similar to the rate (0.60 d^{-1}) determined for that compound in the overlying water of spiked sediment (Ciarelli et al. 2000). Rapid elimination of PAHs has been reported for other species of polychaetes (e.g., Christensen et al. 2002). The limited kinetics information derived in this study indicates that PAHs approached steady state rapidly (TSS in 6 to 15 days) in *N. virens* exposed to the two sediments. Such rapid acquisition of steady state is consistent with previous reports for different species of polychaetes (Augenfeld et al. 1982; Ciarelli et al. 2000; Christensen et al. 2002).

The elimination rates estimated for the Newark Bay sediment exposures were relatively similar, ranging from 0.089 to 0.2143 d^{-1} (Table C4; Figure 23). Rates estimated for the Arthur Kill sediment were consistently lower, suggesting that temporal changes in the uptake kinetics determined for the Arthur Kill sediment (e.g., increased uptake rate during the later exposure period) may have been responsible for the unexpectedly low elimination rates. PAHs approached steady state much more slowly in *M. nasuta* ($TSS_{95\%}$ in 14 to 131 days) compared to *N. virens* (Figure 24). Due to the different temporal patterns of bioaccumulation, the TSS was unexpectedly high for pyrene (72 days), chrysene (131 days), and benzo[b]fluoranthene (94 days) compared to values derived from the Newark Bay exposure (18, 34, and 18 days, respectively). The ASTM (2000) reports that *M. nasuta* reached 100% of steady state for benzo(b,k) fluoranthene and fluoranthene after 28 days of exposure. That determination is much more comparable to results for $TSS_{95\%}$ for PAHs in exposure to Newark Bay sediment (92–100%) than the exposure to Arthur Kill sediment (47–93%) (Table 4). Results derived from the Newark Bay sediment exposure are expected to be more representative of the temporal pattern of PAH accumulation in *M. nasuta*. Laboratory exposures to a wider variety of sediments would be necessary to determine the adequacy of the 28-d exposure duration for determined steady-state concentrations of PAHs in *M. nasuta*.

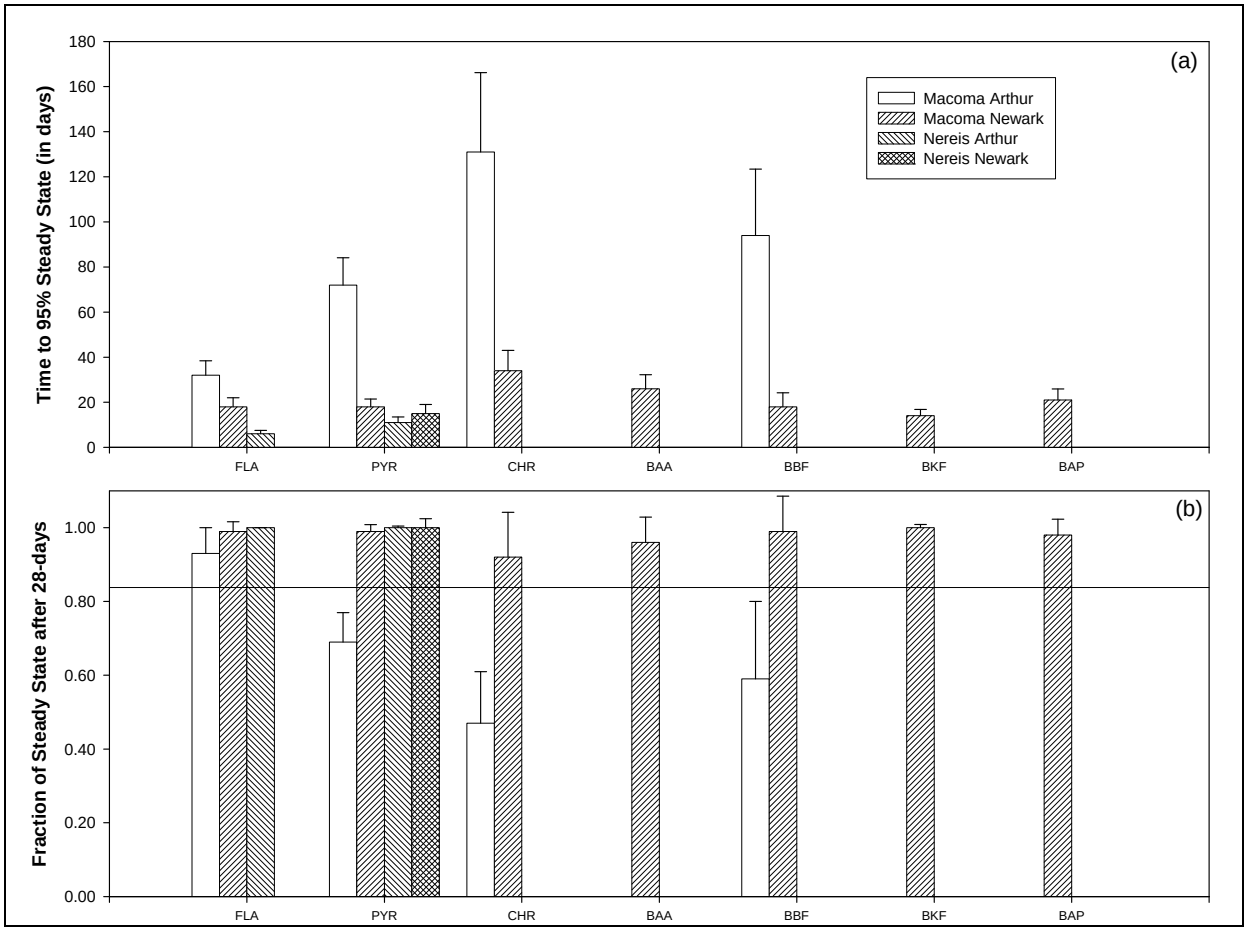

Figure 24. Time to 95% steady state (TSS) (a) and fraction of steady state ($f_{ss\text{-}28d}$) (b) derived for PAHs in *Macoma nasuta* and *Nereis virens* in this study. The solid line in panel b indicates 80% of steady state.

The PAH compounds have relatively low log K_{ow} values from 3.34–6.04 and the data set allowed only three data points to be plotted for *N. virens*, both of which reached more than 80% steady-state tissue residues (Figure 25). Compounds with log K_{ow} values greater than 5.5 did not reach 80% of steady state in *M. nasuta* tissue only in the Arthur Kill exposure.

For *N. virens*, the 28-d and steady-state BSAFs were similar among congeners and between the Arthur Kill and Newark Bay sediment exposures (Table B4; Figure 26). The BSAFs obtained in this study were substantially lower compared to mean values (0.80–3.31) reported by Brannon et al. (1993) using total radioactivity rather than measured parent compound concentration.

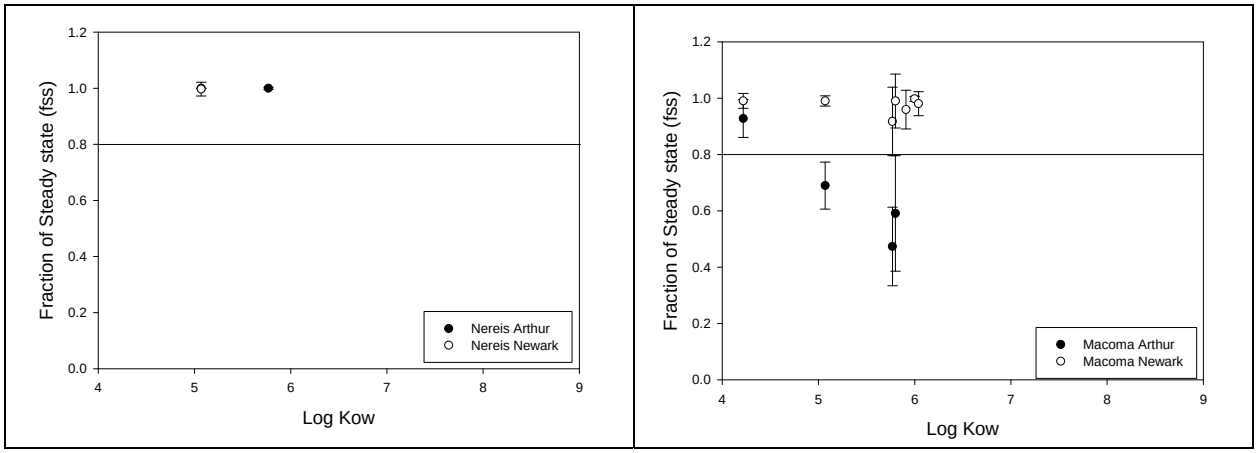

Figure 25. Log K_{ow} versus 28-d fraction of steady state (f_{ss}) for (a) *Nereis virens* (triangles) and (b) *Macoma nasuta* (circles) exposed in the Arthur Kill (filled points) and Newark Bay (open points) sediment. Error bars indicate standard error. The horizontal line indicates 80% of steady state.

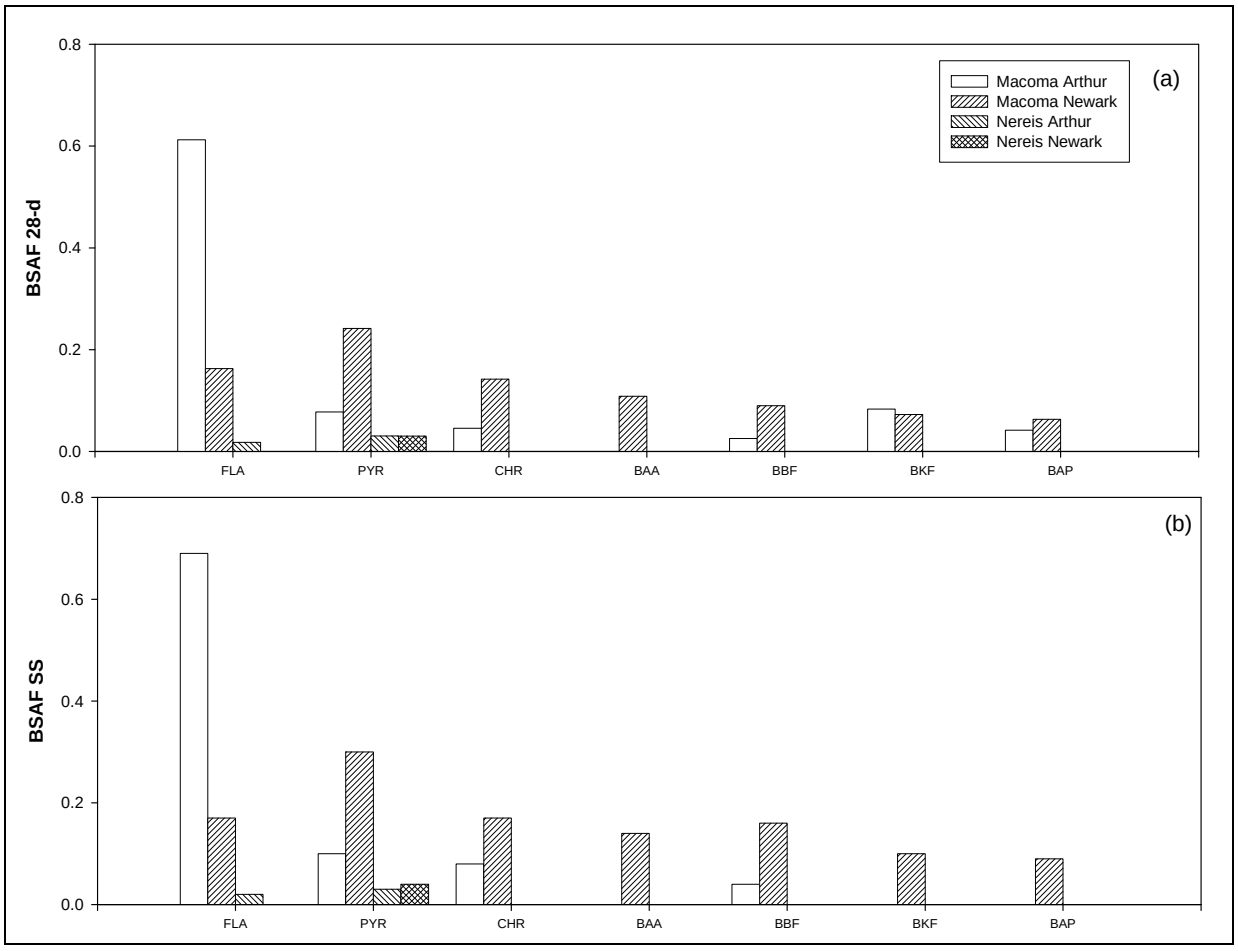

Figure 26. Mean instantaneous 28-d biota-to-sediment accumulation factors (BSAF) (a), and kinetically modeled at steady state BSAF at steady state (BSAF SS) (b) biota-to-sediment accumulation factors for *Nereis virens* and *Macoma nasuta* exposed to the Arthur Kill sediment. FLA = fluoranthene; PYR = pyrene; CHR = chrysene; BAA = benzo[a]anthracene; BBF = benzo[b]fluoranthene, benzo[k]fluoranthene, BAP = benzo[a]pyrene.

For *M. nasuta*, the 28-d and steady-state BSAFs were similar among congeners for the Newark Bay sediment. The BSAF values were substantially lower for the Arthur Kill sediment except for fluoranthene (Table C4; Figure 26), consistent with similar data determined for PCBs. The BSAF values determined for the Newark Bay site were similar to values reported by Ferraro et al. (1990).

A limitation of this study was that it was only possible to assess a small number of PAHs since many of the uptake curves did not fit the steady-state model (Equation 1). Curves for other PAHs were not obtained due to insufficient or unstable concentrations in the tested sediments or due to the metabolism of the test organisms, particularly *N. virens* (Ernst et al. 1977; Driscoll and McElroy 1996; Goerke and Weber 2001; Rust et al. 2004). Additionally, alkylated PAHs and PAH metabolites were not considered in the analysis.

Mercury and methyl mercury

Mercury sediment chemistry (Table A5), kinetics information (Tables B5 and C5), and uptake curves (Figures D5 and E5) are summarized in the appendices.

Methyl mercury approached steady state in *N. virens* and *M. nasuta* in 28 days or less of exposure in both test sediments. Mercury approached steady state in *N. virens* before 28 days of exposure in both experiments while steady state occurred after 28 days in *M. nasuta* in both experiments. Thus, standard 28-d bioaccumulation test duration appears adequate for *N. virens* and *M. nasuta* for steady-state bioaccumulation determination of methyl mercury, but longer exposure duration is required for *M. nasuta* for steady-state bioaccumulation determination of mercury from New York Harbor sediments.

Non-model-conforming patterns of bioaccumulation prevented determination of uptake kinetics rates for mercury and methyl mercury in *N. virens* exposed to the Newark Bay and for methyl mercury in *M. nasuta* exposed to the Arthur Kill sediment (Tables B5 and C5, Appendices D and E). For *M. nasuta*, uptake and elimination parameters for mercury were similar in both the Arthur Kill and Newark Bay sediments. The rates of uptake were similar for methyl mercury and mercury while elimination was faster for methyl mercury in the Newark Bay sediment. For *N. virens*, the uptake rate was substantially higher for mercury while the rates of

elimination were similar for both compounds in the Arthur Kill sediment. The temporal pattern of mercury bioaccumulation was investigated in *M. nasuta* and *N. virens* exposed to sediment collected from the Hamilton Airfield tidal wetland (San Francisco Bay) Bay Edge location (Best et al. 2005, 2007). Although all the *M. nasuta* and most of the *N. virens* exposures to HAAF sediment resulted in non-model conforming patterns of bioaccumulation, overall temporal trends in bioaccumulation clearly indicated that apparent steady-state body burden was not reached following a 56-d exposure. An elimination rate of 0.0189 d^{-1}reported for *N. virens* from uptake curve fitting is associated with an estimated time to 95% steady state of 159 days. Furthermore, the final body burdens (56 days) of the experimentally exposed clams and worms were less than 50% of those recorded in benthic invertebrates collected from the source site for sediment, further suggesting that long exposure periods are needed for total mercury and methyl mercury to approach apparent steady state in *N. virens* and *M. nasuta*. Consequently, the elimination rates obtained in this study for *M. nasuta* and *N. virens* are likely artificially fast due to lack of temporal bioaccumulation trends resulting from variability between samples (Figure D9). The slow elimination rates reported above are additionally problematic since methyl mercury integrates readily into cytoplasm, making it a strong candidate for biomagnification up the food chain (Mason et al. 1996; Wiener et al. 2003).

The BSAF approach is not applicable to MeHg (Bridges et al. 1996) and therefore, BSAF values are not reported in this study.

Relationship to K_{ow}

Theoretically, the time needed to reach steady state should increase for compounds with log K_{ow} values between 5 and 7 and decrease for compounds with log K_{ow} values between 7 and 10. This is illustrated in Figure 27 from McFarland (1995). Since the compound with the highest K_{ow} value tested in this study was 8.75 (OCDD), the entire increasing trend shown on the right-hand side of Figure 27 was not addressed. This relationship does not account for differences in bioavailability or metabolism.

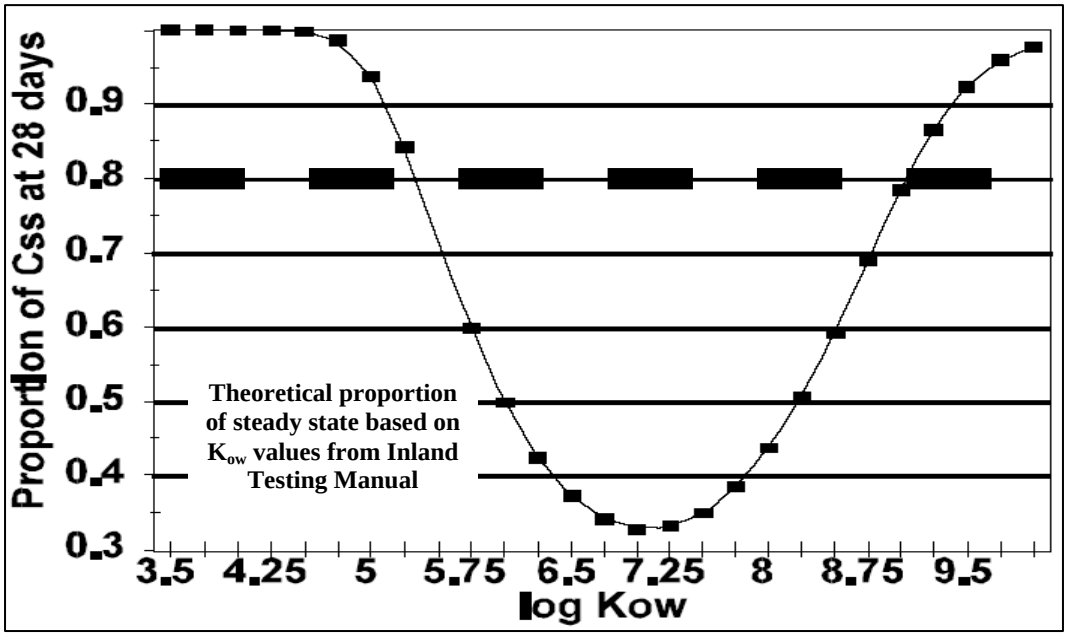

Figure 27. Theoretical relationship between log K_{ow} and steady-state concentration from USEPA/USACE (1998).

Plots of log K_{ow} vs. the 28-day f_{ss} for both organisms did not closely represent this theoretical pattern (Figure 28). However, a loose resemblance is observed for the Arthur Kill Points (solid plots), most notably for *M. nasuta* (solid circles). For *N. virens*, since most compounds reached steady state within 28 days, no trend was observed. It is clear that fewer compounds reached 80% steady state in tissues in the Arthur Kill exposure (filled points) for both organisms (K_{ow} 6–8.75), while only some dioxins and furans in the Newark Bay exposure with K_{ow} values >8.0 did not reach steady state (mostly in *M. nasuta* tissue). No compound with a K_{ow} >8.0 reached 80% steady state in *M. nasuta* tissue in either test sediment.

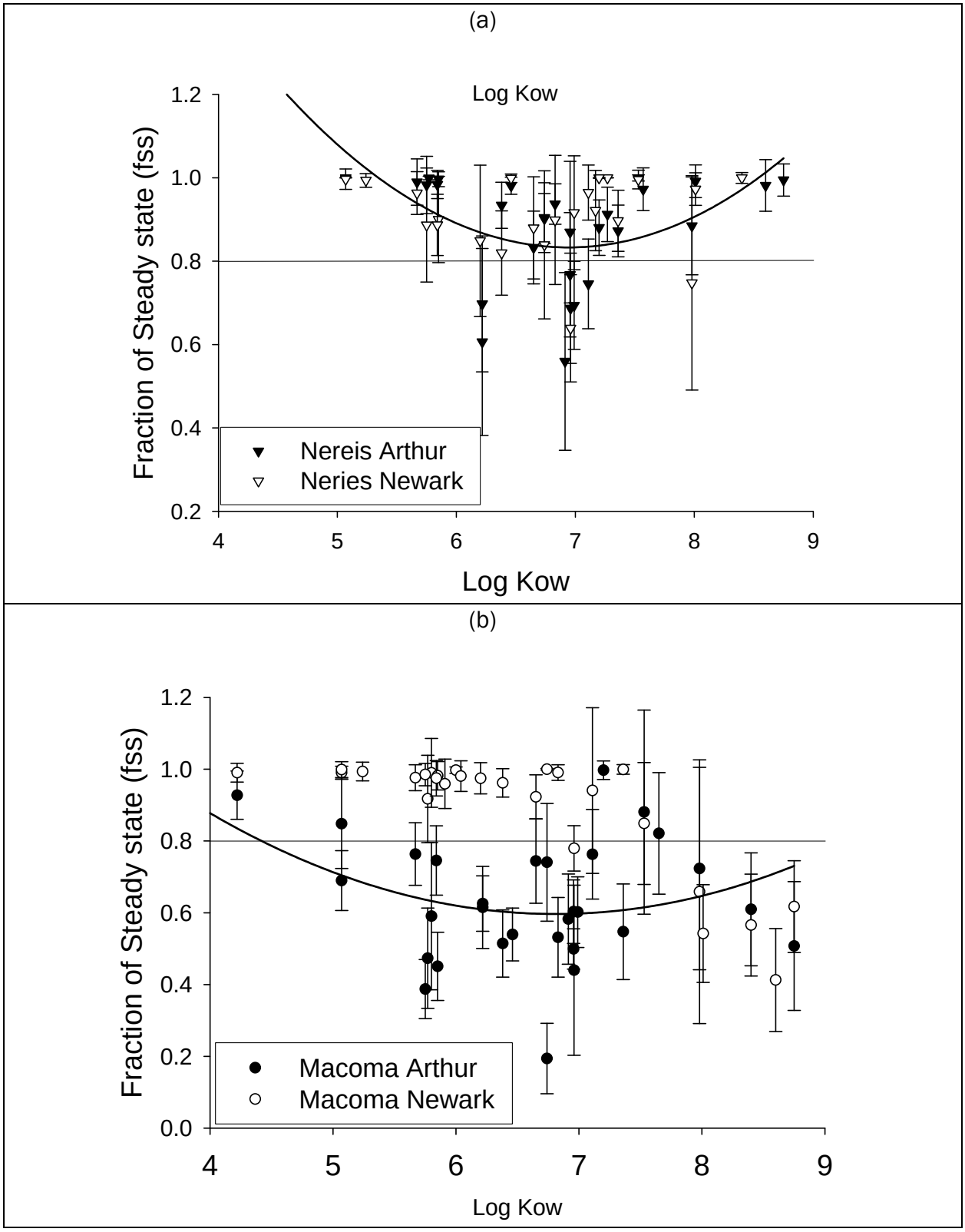

Figure 28. Plots of fraction of steady state after 28-d exposure versus log K_{ow} values for *Nereis virens* (a) and *Macoma nasuta* (b).

4 Conclusions and Recommendations

The approach used in this study to derive steady-state concentrations is recommended in guidance documents (ASTM 2000; USEPA/USACE 1998). The authors recommend the kinetic method over the operational/ statistical method for assessing steady-state bioaccumulation in sediment bioaccumulation exposures. Results from this study and the other studies published in the available literature indicate that the time to steady-state tissue residues in laboratory exposure to contaminated sediments is both compound- and organism-specific. While tissue residues were generally greater for *N. virens*, time to steady state was generally greater for the clam *M. nasuta* for most compounds. Overall, the 28-d sediment exposure duration appears adequate for many chemicals to reach at least 80% steady-state tissue residue in *N. virens* but not *M. nasuta*, with the caveat that only two sediments were tested in this study.

For *N. virens*, the results suggest the standard 28-d bioaccumulation test duration is adequate to obtain 80% of steady state for PCBs, and most dioxins and furans. However, greater than 28 days may be required for DDTs and some dioxins and furans (e.g., TCDD, TCDF, and PeCDF; Appendix B3). While the *N. virens* uptake curves (Appendix D) for PAHs in this study did suggest steady state was rapid (within days; Appendix B), the polychaete worm is probably not an appropriate model species to acquire a conservative estimate of PAH bioaccumulation due to rapid biotransformation of the parent compound (Rust et al. 2004).

For *M. nasuta*, results of this study (Table 4) and information available in the peer-reviewed literature suggest that sediment exposures longer than 28 days are probably required for DDTs, most PCBs, and most dioxins/ furans. The data suggested 28-d duration, however, was adequate for PAHs due to greater elimination rates. *Macoma nasuta* is a better candidate than *N. virens* to conservatively estimate the potential for PAH bioaccumulation from sediments.

Although data from this study indicate that the 28-d exposures would be adequate for deriving methyl mercury and total mercury steady-state tissue residues for New York Harbor sediments, previous investigations indicated that only a fraction of 0.42 of the predicted steady-state residues

of those compounds may accumulate in the tissues of *M. nasuta* and *N. virens* after 28 days. Therefore, the conservative use of a multiplier of 2 is recommended based on previous investigations (Best et al. 2005, 2007) until an improved understanding of the toxicokinetics of mercury and methyl mercury in *N. nasuta* and *N. virens* is obtained.

The temporal pattern of bioaccumulation and consequently the time to approach steady state for several PCBs and dioxin congeners were substantially different between sediments. The nonlinear model was used to estimate the elimination rate with the assumption that the uptake rate is constant throughout the entire duration of the experiment; a decrease of uptake rate with time would result in a slower increase in tissue residues towards the end of the experiment, which forces the uptake curve toward an asymptote, resulting in inaccurately high estimates of the elimination rate. It is possible that the *M. nasuta* uptake rate for PCBs in the Newark Harbor sediment decreased over time leading to a lower than expected temporal increase in tissue residue and consequently higher estimated elimination rates. This, in turn, projected a lower time to steady state. The rates of elimination and time to steady state of PCBs in *M. nasuta* derived for the Arthur Kill sediment exposure more closely agree with those previously reported by Boese et al. (1995, 1997).

For compounds that require more than 28 days to reach at least 80% of steady state (Table 4), the most accurate method for determining steady-state tissue residues on a case-by-case basis would be to extend the duration of bioaccumulation tests. However, the elevated cost, increased time, labor and sediment requirements of such tests will likely make this impossible for many projects. Another option is to apply steady-state correction factors (i.e., the reciprocal of the 28-d fraction of steady state; 1/28-d f_{ss}) to estimate steady-state bioaccumulation from standard 28-d bioaccumulation test results (see Figure 6-1 in USEPA/USACE 1998). Results obtained from this study may be used to derive such organism- and compound-specific correction values by taking the reciprocal of the fraction of steady state at 28 days (f_{ss}) reported in Table 4 and Appendices B and C. This factor could be used as a multiplier to estimate steady state from actual 28-d bioaccumulation test residues.

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Appendix A: Sediment Chemistry

Table A1. Sediment chemistry data for dichloro-diphenyl-trichloroethane (DDTs) (µg/kg).

Analyte	Arthur
pp-DDD	119.2
pp-DDE	122.2
pp-DDT	107.5
op-DDE	57.6
op-DDD	32.9

Table A2. Sediment chemistry data for polycarbonated biphenyl (PCB) congeners (µg/kg). NR = not reported.

Congener	Arthur	Newark
8	4.59	4.59
18	<0.79	0.395
28	14.3	14.3
44	12.6	12.6
49	12.5	12.5
52	22.886	22.886
66	15.648	15.648
77	<0.79	<0.79
81	<0.79	<0.79
87	<0.79	<0.79
101	15.178	15.178
105	4.232	4.232
114	0.471	0.471
118	13.445	13.445
123	<0.79	<0.79
126	<0.79	<0.79
128	2.559	2.559
138	13.637	13.637
153	NR	NR
156	<0.79	<0.79
157	<0.79	<0.79
167	0.934	0.934
169	<0.79	<0.79
170	2.933	2.933
180	6.5	6.5
183	2.694	2.694
184	<0.79	<0.79
187	5.035	5.035
189	<0.79	<0.79
195	0.639	0.639
206	1.882	1.882
209	2.82	2.82

Table A3. Sediment chemistry data for dioxins and furans (pg/g).

Analyte	Arthur	Newark
2,3,7,8-TCDD	7.6	14
TOTAL TCDD	48	19
1,2,3,7,8-PeCDD	2.3	1.8
TOTAL PeCDD	48	130
1,2,3,4,7,9-HxCDD	3	1.2
1,2,3,6,7,8-HxCDD	14	6
1,2,3,7,8,9-HxCDD	11	4
TOTAL HxCDD	140	69
1,2,3,4,6,7,8-HpCDD	170	110
TOTAL HpCDD	390	380
OCDD	2300	1000
2,3,7,8-TCDF	38	3.9
TOTAL TCDF	230	44
1,2,3,7,8,-PeCDF	9.4	2.8
2,3,4,7,8-PeCDF	12	3.9
TOTAL PeCDF	180	65
1,2,3,4,7,8-HxCDF	41	18
1,2,3,6,7,8-HxCDF	12	3.9
2,3,4,6,7,8-HxCDF	10	2.3
1,2,3,7,8,9-HxCDF	1.8	0.65
TOTAL HxCDF	180	79
1,2,3,4,6,7,8-HpCDF	120	89
1,2,3,4,7,8,9-HpCDF	14	4.3
TOTAL HpCDF	210	130
OCDF	200	210

Table A4. Sediment chemistry data for polycyclic aromatic hydrocarbons (PAHs) (µg/kg).

Analyte	Arthur	Newark
(290) NAPHTH	255	168
(294) ACENAY	28.0	19.6
(296) ACENAP	63.2	175
(297) FLUORE	103	153
(303) PHENAN	775	581
(304) ANTRAC	282	327
(306) FLANTHE	2210	1640
(307) PYRENE	2190	1230
(309) CHRYSE	902	775
(310) BAANTHR	706	646
(313) BBFLANT	1360	435
(314) BKFLANT	434	413
(315) BAPYRE	866	550
(316) I123PYR	800	336
(317) DBAHANT	147	84.5
(318) B-GHI-PY	676	398
(322) 2MeNAPH	141	102
(327) 2FIBP-S	66.4%	64.0%
(328) PTERP-S	85.4%	84.0%

Appendix B: Summary of Kinetic Parameters Derived for *Nereis virens*

Table B1. Modeled output for *Nereis virens* exposed to 1,1,1-tricrichloro-2,2-bis(p-chlorophenyl)ethane (DDT), 1,1-dichloro-2,2-bis(p-chlorophenyl) ethylene (DDE) and 1,1-dichloro-2,2-bis(p-chlorophenyl)ethane (DDD). The steady-state concentration by the operation method is shown for both the first and last sets of three consecutive time points.

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{ss} (µg/kg)	Statistical C_{ss} (µg/kg) First 3 pts	Statistical C_{ss} (µg/kg) Last 3 pts	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{ss}$
p,p-DDD	Arthur	6.22	0.0110 ± 0.0028*	0.0333 ± 0.0161#	90	0.61	119.2	23.9	37.4	4.8 ± 2.8	30.8 ± 2.7	0.42	0.33	0.51
o,p-DDD	Arthur	6.22	0.0111 ± 0.0024*	0.0427 ± 0.0154*	70	0.70	32.9	6.0	8.1	7.3 ± 0.7	7.3 ± 0.7	0.34	0.30	0.40
p,p-DDT	Arthur	6.91	0.0040 ± 0.0009*	0.0293 ± 0.0141#	102	0.56	107.5	8.2	13.9	10.5 ± 1.2	10.5 ± 1.2	0.14	0.12	0.21
p,p-DDE	Arthur	6.95	0.0101 ± 0.0031*	0.0728 ± 0.0298*	41	0.87	122.2	14.7	16.1	5.6 ± 2.4	16.6 ± 3.0	0.25	0.20	0.21
o,p-DDE	Arthur	6.95	0.0031 ± 0.0007*	0.0521 ± 0.0177*	58	0.77	57.6	2.6	3.3	0.9 ± 0.3	3.0 ± 0.3	0.09	0.07	0.09
Total DDT	Arthur	NA	0.0070 ± 0.0015*	0.0353 ± 0.0142*	85	0.63	439.4	54.7	82.8	12.4 ± 6.1	69.0 ± 4.8	0.25	0.20	0.31

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

Table B2. Modeled output for *Nereis virens* exposed to polychlorinated biphenyls (PCBs).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
PCB 18	Newark	5.24	0.4771 ± 0.1086*	0.1823 ± 0.0467*	17	0.99	0.4†	1.0	1.0	NA	NA†	4.71
PCB 28	Arthur	5.67	0.0187 ± 0.0067*	0.1642 ± 0.0669#	18	0.99	16.1	1.8	1.7	0.24	0.18	0.18
PCB 28	Newark	5.67	0.0092 ± 0.0020*	0.1181 ± 0.0313*	25	0.96	14.3	1.1	1.1	NA	0.10	0.10
PCB 44	Arthur	5.75	0.0155 ± 0.0053*	0.1450 ± 0.0574#	21	0.98	17.3	1.8	1.8	0.21	0.17	0.17
PCB 44	Newark	5.75	0.0040 ± 0.0012*	0.0778 ± 0.0283*	39	0.89	12.6	0.6	0.6	0.04	0.06	0.06
PCB 49	Arthur	5.85	0.0214 ± 0.0063*	0.2032 ± 0.0658*	15	1.00	16.1	1.7	1.6	0.20	0.17	0.16
PCB 49	Newark	5.85	0.0074 ± 0.0018*	0.0823 ± 0.0254*	37	0.90	12.5	1.0	1.1	0.08	0.11	0.11
PCB 52	Arthur	5.84	0.0304 ± 0.0073*	0.1482 ± 0.0410*	20	0.98	20.6	4.2	4.0	0.37	0.33	0.32
PCB 52	Newark	5.84	0.0079 ± 0.0014*	0.0779 ± 0.0179*	39	0.89	22.9	2.1	2.2	0.13	0.12	0.13
PCB 66	Newark	6.20	0.0080 ± 0.0025*	0.0675 ± 0.0282*	44	0.85	15.6	1.6	1.8	0.06	0.13	0.15
PCB 101	Arthur	6.38	0.0273 ± 0.0050*	0.0972 ± 0.0218*	31	0.93	17.3	4.5	4.6	0.36	0.43	0.43
PCB 101	Newark	6.38	0.0108 ± 0.0020*	0.0612 ± 0.0159*	49	0.82	15.2	2.2	2.5	0.15	0.19	0.22
PCB 105	Arthur	6.65	0.0155 ± 0.0026*	0.0639 ± 0.0150*	47	0.83	3.5	0.7	0.8	0.34	0.33	0.38
PCB 105	Newark	6.65	0.0092 ± 0.0023*	0.0757 ± 0.0251*	40	0.88	4.2	0.5	0.5	0.10	0.14	0.15
PCB 118	Arthur	6.74	0.0117 ± 0.0024*	0.0839 ± 0.0225*	36	0.90	12.3	1.6	1.6	0.25	0.21	0.22
PCB 118	Newark	6.74	0.0049 ± 0.0014*	0.0653 ± 0.0266*	46	0.84	13.4	0.8	1.0	0.07	0.08	0.09
PCB 128	Arthur	6.74	0.0132 ± 0.0021*	0.0830 ± 0.0171*	36	0.90	2.8	0.4	0.4	0.24	0.23	0.25
PCB 138	Arthur	6.83	0.0230 ± 0.0038*	0.0988 ± 0.0204*	30	0.94	14.1	3.1	3.1	0.36	0.36	0.36

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
PCB 138	Newark	6.83	0.128 ± 0.0040*	0.0819 ± 0.0332*	37	0.90	13.6	1.9	2.0	0.21	0.18	0.19
PCB 170	Arthur	7.27	0.0137 ± 0.0025*	0.0870 ± 0.0199*	35	0.91	3.1	0.4	0.5	0.23	0.23	0.24
PCB 170	Newark	7.27	0.0680 ± 0.0256*	0.6374 ± 0.2477*	5	1.00	2.9	0.3	0.3	0.14	0.14	0.13
PCB 180	Arthur	7.36	0.0118 ± 0.0017*	0.0736 ± 0.0142*	41	0.87	8.2	1.1	1.2	0.23	0.23	0.25
PCB 180	Newark	7.36	0.0099 ± 0.0018*	0.0812 ± 0.0192*	37	0.90	0.7	0.1	0.1	NA	0.14	0.15
PCB 183	Arthur	7.20	0.0180 ± 0.0028*	0.0759 ± 0.0158*	40	0.88	2.3	0.5	0.5	0.35	0.34	0.37
PCB 183	Newark	7.20	0.0424 ± 0.0109*	0.3340 ± 0.0911*	9	1.00	2.7	0.3	0.3	0.17	0.17	0.16
PCB 187	Newark	7.17	0.0139 ± 0.0035*	0.0909 ± 0.0286*	33	0.92	5.0	0.7	0.7	0.16	0.18	0.19

* Significance ($p < 0.05$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

TSS = time to 95% steady state

28-d f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

† Sediment concentration less than detection limit (<0.79), therefore half the detection limit was used.

Table B3. Modeled output for *Nereis virens* exposed dioxins and furans.

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (pg/g)	C_{28} (pg/g)	Kinetic C_{SS} (pg/g)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
2,3,7,8-TCDD	Arthur	6.96	0.0136 ± 0.0023*	0.0415 ± 0.0126*	72	0.69	7.6	1.7	2.4	0.40	0.37	0.51
2,3,7,8-TCDD	Newark	6.96	0.0099 ± 0.0016*	0.0364 ± 0.0109*	82	0.64	14.0	2.4	3.6	0.22	*0.23*	*0.34*
Total TCDD	Arthur	NA	0.0086 ± 0.0025*	0.0999 ± 0.0367*	30	0.94	48.0	3.9	3.9	0.13	0.13	0.13
Total TCDD	Newark	NA	0.0226 ± 0.0033*	0.0523 ± 0.0117*	57	0.77	19.0	6.3	7.8	0.36	*0.43*	*0.53*
Total PeCDD	Newark	NA	0.0006 ± 0.0002*	NC	NC	NC	130	NC	NC	0.02	NC	NC
123678 HxCDD	Arthur	7.98	0.0042 ± 0.0010*	0.0772 ± 0.0251*	39	0.88	14.0	0.7	0.7	0.08	0.08	0.08
123678 HxCDD	Newark	7.98	0.0044 ± 0.0014*	0.0492 ± 0.0251#	61	0.75	6.0	0.4	0.5	0.07	*0.09*	*0.11*
Total HxCDD	Arthur	NA	0.0045 ± 0.0012*	0.0880 ± 0.0293*	34	0.91	140.0	6.5	6.8	0.12	0.08	0.08
Total HxCDD	Newark	NA	0.0070 ± 0.0023*	0.0777 ± 0.0337*	39	0.89	69.0	5.5	5.9	0.07	*0.10*	*0.11*
1,2,3,4,6,7,8-HpCDD	Arthur	8.4	0.0036 ± 0.0010*	0.1821 ± 0.0580*	17	0.99	170.0	3.3	3.2	0.04	0.03	0.03
1,2,3,4,6,7,8-HpCDD	Newark	8.4	0.0094 ± 0.0048#	0.3414 ± 0.1866#	9	1.00	110.0	3.0	2.9	0.03	*0.04*	*0.03*
TOTAL HpCDD	Arthur	NA	0.0047 ± 0.0017*	0.1419 ± 0.0588*	21	0.98	390.0	12.7	12.3	0.04	0.05	0.05
OCDD	Arthur	NA	0.0023 ± 0.0009*	0.1883 ± 0.0765*	16	0.99	2300.0	27.9	26.7	0.02	0.02	0.02
2,3,7,8-TCDF	Arthur	6.46	0.0179 ± 0.0029*	0.1417 ± 0.0263*	21	0.98	38.0	4.7	4.6	0.21	0.20	0.20
2,3,7,8-TCDF	Newark	6.46	0.1225 ± 0.0394*	0.2474 ± 0.0873*	12	1.00	3.9	1.9	1.8	0.87	*0.64*	*0.61*
Total TCDF	Arthur	NA	0.0340 ± 0.0156*	0.3081 ± 0.1515#	10	1.00	230.0	25.4	24.1	0.19	0.18	0.17
Total TCDF	Newark	NA	0.1582 ± 0.0354*	0.1189 ± 0.0318*	25	0.96	44.0	56.4	55.6	1.48	*1.67*	*1.65*
1,2,3,7,8,-PeCDF	Arthur	6.99	0.0094 ± 0.0014*	0.0423 ± 0.0106*	71	0.69	9.4	1.4	2.0	0.24	0.25	0.34
1,2,3,7,8,-PeCDF	Newark	6.99	0.0190 ± 0.0058*	0.0886 ± 0.0346*	34	0.92	2.8	0.6	0.6	0.25	*0.26*	*0.27*
2,3,4,7,8-PeCDF	Arthur	7.11	0.0087 ± 0.0014*	0.0489 ± 0.0126*	61	0.75	12.0	1.6	2.0	0.22	0.22	0.28
2,3,4,7,8-PeCDF	Newark	7.11	0.0195 ± 0.0052*	0.1195 ± 0.0377*	25	0.96	3.9	0.6	0.6	0.21	*0.20*	*0.20*

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (pg/g)	C_{28} (pg/g)	Kinetic C_{SS} (pg/g)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
TOTAL PeCDF	Arthur	NA	0.0120 ± 0.0022*	0.0998 ± 0.0223*	30	0.94	180.0	20.3	20.6	0.19	0.18	0.19
TOTAL PeCDF	Newark	NA	0.0644 ± 0.0142*	0.1457 ± 0.0373*	21	0.98	65.0	28.2	27.3	0.49	*0.57*	*0.55*
1,2,3,4,7,8-HxCDF	Arthur	7.53	0.0102 ± 0.0041*	0.3042 ± 0.1300*	10	1.00	41.0	1.4	1.3	0.04	0.05	0.05
1,2,3,4,7,8-HxCDF	Newark	7.53	0.0138 ± 0.0042 *	0.1959 ± 0.0663*	15	1.00	18.0	1.3	1.2	0.08	*0.09*	*0.09*
1,2,3,6,7,8-HxCDF	Arthur	7.57	0.0060 ± 0.0015*	0.1284 ± 0.0376*	23	0.97	12.0	0.5	0.5	0.08	0.07	0.07
1,2,3,4,6,7,8-HpCDF	Arthur	8.01	0.0024 ± 0.0008*	0.1717 ± 0.0627*	18	1.00	120.0	1.7	1.6	0.02	0.02	0.02
1,2,3,4,6,7,8-HpCDF	Newark	NA	0.0019 ± 0.0004*	0.1291 ± 0.0320*	23	0.97	89.0	1.3	1.2	0.02	*0.02*	*0.02*
TOTAL HpCDF	Arthur	NA	0.0066 ± 0.0033#	0.4665 ± 0.2482#	6	1.00	210.0	3.0	2.8	0.01	0.02	0.02
OCDF	Arthur	8.60	0.0018 ± 0.0006*	0.1431 ± 0.0529*	21	0.98	200.0	2.5	2.4	0.02	0.02	0.02

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

K_{ow} values from Govers and Krop (1998)

Table B4. Modeled output for *Nereis virens* exposed to polycyclic aromatic hydrocarbons (PAHs).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
FLA†	Arthur	4.22	0.0063 ± 0.0021*	0.5426 ± 0.1936*	6	1.00	2210	25.7	24.4	0.02	0.02	0.02
PYR†	Arthur	5.07	0.0052 ± 0.0014*	0.2782 ± 0.086*	11	1.00	2190	40.9	38.9	0.02	0.03	0.03
PYR	Newark	5.07	0.0066 ± 0.0022*	0.2060 ± 0.0776*	15	1.00	1230	39.3	34.7	0.03	0.04	0.04

* Significance ($p < 0.05$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

† 56-d time point excluded due to bad analytical data

Table B5. Modeled output for *Nereis virens* exposed to mercury (Hg) and methyl mercury (Me-Hg). Results were unavailable in the Newark Bay treatment due to failure of temporal data to fit the steady-state model (Equation 1).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed}	C_{28}	Kinetic C_{SS}
Hg	Arthur	NA	0.4082 ± 0.1706*	0.4432 ± 0.1959*	7	1.00	0.0468	0.0043	0.0041
Me-Hg	Arthur	NA	0.0678 ± 0.0381#	0.8179 ± 0.4727#	4	1.00	43.1 μg/kg	3.6 μg/kg	3.4 μg/kg

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

Appendix C. Summary of Kinetic Parameters Derived for *Macoma nasuta*

Table C1. Modeled output for *Macoma nasuta* exposed to 1,1,1-tricrichloro-2,2-bis(p-chlorophenyl)ethane (DDT), 1,1-dichloro-2,2-bis(p-chlorophenyl)ethylene (DDE) and 1,1-dichloro-2,2-bis(p-chlorophenyl)ethane (DDD).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Statistical C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
p,p-DDD	Arthur	6.22	0.0048 ± 0.0007 *	0.0351 ± 0.0067 *	86	0.63	119.2	10.2	15.5	15.8 ± 1.5	0.16	0.19	0.29
o,p-DDD†	Arthur	6.22	0.0040 ± 0.0008 *	0.0341 ± 0.0093 *	88	0.62	32.9	2.4	3.7	3.7 ± 0.2	0.16	0.16	0.25
p,p-DDT	Arthur	6.91	0.0009 ± 0.0002 *	0.0312 ± 0.0094 *	96	0.58	107.5	1.8	2.9	3.1 ± 0.2	0.03	0.04	0.06
p,p-DDE	Arthur	6.95	0.0035 ± 0.0004 *	0.0247 ± 0.0038 *	122	0.50	122.2	8.6	16.5	15.3 ± 1.5	0.15	0.16	0.30
o,p-DDE	Arthur	6.95	0.0033 ± 0.0005 *	0.0330 ± 0.0072 *	91	0.60	57.6	3.5	5.5	5.4 ± 0.5	0.13	0.13	0.21
Total DDT	Arthur	NA	0.0031 ± 0.0004 *	0.0293 ± 0.0046 *	102	0.56	439.4	26.0	44.2	43.2 ± 1.0	0.12	0.13	0.22

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

TSS95% = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

† 10-d time point excluded (very high outlier)

Table C2. Modeled output for *Macoma nasuta* exposed to polychlorinated biphenols (PCBs).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
PCB 8	Arthur	5.24	0.0076 ± 0.0021*	0.0673 ± 0.0214*	44	0.85	3.9	0.4	0.4	0.27	0.21	0.24
PCB 18	Newark	5.24	0.5956 ± 0.2523*	0.2468 ± 0.1119*	12	1.00	0.4†	1.0	0.9	7.35	4.78	4.54
PCB 28	Arthur	5.67	0.0063 ± 0.0012*	0.0515 ± 0.0112*	58	0.76	16.1	1.5	1.9	0.25	0.21	0.26
PCB 28	Newark	5.67	0.0236 ± 0.0070*	0.1809 ± 0.0583*	17	0.99	14.3	1.9	1.8	0.17	0.26	0.25
PCB 44	Arthur	5.75	0.0021 ± 0.0003*	0.0175 ± 0.0045*	40	0.39	17.3	0.8	2.0	0.13	0.10	0.25
PCB 44	Newark	5.75	0.0123 ± 0.0028*	0.1339 ± 0.0332*	22	0.98	12.6	1.1	1.1	0.17	0.18	0.17
PCB 49	Arthur	5.85	0.0035 ± 0.0006*	0.0214 ± 0.0057*	140	0.45	13.5	1.0	2.1	0.20	0.16	0.35
PCB 49	Newark	5.85	0.0252 ± 0.0062*	0.1504 ± 0.0403*	20	0.99	12.5	2.1	2.0	0.25	0.33	0.32
PCB 52	Arthur	5.84	0.0076 ± 0.0015*	0.0489 ± 0.0115*	61	0.75	20.6	2.4	3.0	0.31	0.26	0.33
PCB 52	Newark	5.84	0.0162 ± 0.0043*	0.1433 ± 0.0414*	21	0.98	22.9	2.5	2.5	0.32	0.22	0.21
PCB 66	Newark	6.20	0.0244 ± 0.0066*	0.1316 ± 0.0388*	23	0.97	15.6	2.8	2.8	0.21	0.36	0.35
PCB 101	Arthur	6.38	0.0072 ± 0.0012*	0.0258 ± 0.0063*	116	0.51	13.0	1.9	3.4	0.40	0.32	0.59
PCB 101	Newark	6.38	0.0246 ± 0.0062*	0.1315 ± 0.0358*	23	0.97	15.2	2.8	2.7	0.33	0.36	0.35
PCB 105	Arthur	6.65	0.0057 ± 0.0013*	0.0487 ± 0.0135*	62	0.74	3.5	0.3	0.4	0.21	0.19	0.25
PCB 105	Newark	6.65	0.0137 ± 0.0027*	0.1166 ± 0.0254*	26	0.96	4.2	0.5	0.5	0.19	0.22	0.22
PCB 118	Arthur	6.74	0.0022 ± 0.0004*	0.0077 ± 0.0041#	390	0.19	12.3	0.7	3.3	0.17	0.12	0.62
PCB 118	Newark	6.74	0.0117 ± 0.0024*	0.0915 ± 0.0209*	33	0.92	13.4	1.6	1.6	0.19	0.23	0.24
PCB 128	Arthur	6.74	0.0039 ± 0.0011*	0.0482 ± 0.0175*	62	0.74	2.8	0.2	0.2	0.12	0.13	0.17
PCB 138	Arthur	6.83	0.0032 ± 0.0006*	0.0271 ± 0.0076*	111	0.53	14.1	0.9	1.6	0.18	0.14	0.25

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
PCB 138	Newark	6.83	0.0113 ± 0.0026*	0.1135 ± 0.0287*	26	0.96	13.6	1.3	1.3	0.16	0.19	0.19
PCB 180	Arthur	7.36	0.0012 ± 0.0003*	0.0283 ± 0.0092*	106	0.55	8.2	0.2	0.3	0.06	0.05	0.09
PCB 180	Newark	7.36	0.0084 ± 0.0020*	0.1674 ± 0.0431*	18	0.99	6.5	0.3	0.3	0.10	0.10	0.09
PCB 183	Arthur	7.20	0.0143 ± 0.0053*	0.2108 ± 0.0838*	14	1.00	2.3	0.2	0.1	0.15	0.15	0.14
PCB 187	Newark	7.20	0.0203 ± 0.0081*	0.2657 ± 0.1131*	11	1.00	5.0	0.4	0.4	0.12	0.15	0.14

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

28-d f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

† Sediment concentration less than detection limit (<0.79), therefore half the detection limit was used.

Table C3. Modeled output for *Macoma nasuta* exposed dioxins and furans.

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (pg/g)	C_{28} (pg/g)	Kinetic C_{SS} (pg/g)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
2,3,7,8-TCDD	Arthur	6.96	0.0072 ± 0.0014*	0.0207 ± 0.0126*	145	0.44	7.6	1.2	2.5	0.38	0.34	0.74
2,3,7,8-TCDD	Newark	6.96	0.0204 ± 0.0029*	0.0540 ± 0.0090*	56	0.78	14.0	4.1	5.0	0.56	0.58	0.71
Total TCDD	Arthur	NA	0.0020 ± 0.0004*	0.0144 ± 0.0367*	208	0.33	48.0	2.2	6.3	0.11	0.10	0.29
Total TCDD	Newark	NA	0.0566 ± 0.0098*	0.0746 ± 0.0149*	40	0.88	19.0	12.4	13.5	1.29	1.29	1.40
123678 HxCDD	Arthur	7.98	0.0026 ± 0.0010*	0.0459 ± 0.0251*	65	0.72	14.0	0.6	0.8	0.13	0.09	0.12
123678 HxCDD	Newark	7.98	0.0058 ± 0.0031#	0.0384 ± 0.0261 P = 0.16	78	0.66	6.0	0.6	0.9	0.20	0.20	0.28
Total HxCDD	Newark	NA	0.0061 ± 0.0020*	0.0493 ± 0.0201*	61	0.75	69.0	6.4	8.1	0.14	0.18	0.23
1,2,3,4,6,7,8-HpCDD	Arthur	8.40	0.0010 ± 0.0003*	0.0336 ± 0.0121*	89	0.61	170.0	3.1	4.8	0.05	0.04	0.06
1,2,3,4,6,7,8-HpCDD	Newark	8.40	0.0036 ± 0.0008*	0.0298 ± 0.0101	101	0.57	110	7.5	12.6	0.12	0.14	0.23
TOTAL HpCDD	Arthur	NA	0.0007 ± 0.0002*	0.0178 ± 0.0085#	169	0.39	390.0	6.0	14.6	0.04	0.03	0.08
TOTAL HpCDD	Newark	NA	0.0028 ± 0.0007*	0.0171 ± 0.0079*	175	0.38	380.0	23.7	59.1	0.12	0.12	0.31
OCDD	Arthur		0.0006 ± 0.0002*	0.0253 ± 0.0111*	119	0.51	2300.0	27.7	51.8	0.03	0.03	0.05
OCDD	Newark		0.0036 ± 0.0008*	0.0343 ± 0.0103*	88	0.62	1000.0	64.8	99.7	0.12	0.13	0.20
2,3,7,8-TCDF	Arthur	6.46	0.0034 ± 0.0005*	0.0277 ± 0.0263*	108	0.54	38.0	2.5	4.4	0.14	0.15	0.26
Total TCDF	Arthur	NA	0.0013 ± 0.0003*	0.0147 ± 0.0053#	204	0.34	230.0	6.9	19.3	0.05	0.07	0.19
Total TCDF	Newark	NA	0.1404 ± 0.0318*	0.0788 ± 0.0200*	38	0.89	44.0	69.8	74.5	2.94	3.14	3.36
1,2,3,7,8,-PeCDF	Arthur	6.99	0.0044 ± 0.0008*	0.0329 ± 0.0079*	91	0.60	9.4	0.8	1.2	0.20	0.18	0.28
2,3,4,7,8-PeCDF	Arthur	7.11	0.0042 ± 0.0010*	0.0514 ± 0.0151*	58	0.76	12.0	0.7	0.9	0.17	0.14	0.17
2,3,4,7,8-PeCDF	Newark	7.11	0.0177 ± 0.0091#	0.1009 ± 0.0567#	30	0.94	3.9	0.6	0.7	0.29	0.33	0.33
TOTAL PeCDF	Newark	NA	0.0307 ± 0.0084*	0.0742 ± 0.0228*	40	0.87	65.0	23.5	25.6	0.60	0.72	0.78

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (pg/g)	C_{28} (pg/g)	Kinetic C_{SS} (pg/g)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
1,2,3,4,7,8-HxCDF	Arthur	7.53	0.0028 ± 0.0014#	0.0759 ± 0.0435*	40	0.88	41.0	1.3	1.4	0.11	0.07	0.08
1,2,3,4,7,8-HxCDF	Newark	7.53	0.0069 ± 0.0024*	0.0675 ± 0.0269*	44	0.85	18.0	1.6	1.7	0.14	0.17	0.19
2,3,4,6,7,8-HxCDF	Arthur	7.65	0.0026 ± 0.0008*	0.0615 ± 0.0238 p = 0.1021	49	0.82	10.0	0.3	0.4	0.11	0.08	0.09
Total HxCDF	Arthur	NA	0.0011 ± 0.0004*	0.0320 ± 0.0146*	94	0.59	180.0	3.7	5.9	0.06	0.05	0.07
Total HxCDF	Newark	NA	0.0107 ± 0.0034*	0.0685 ± 0.0246*	44	0.85	79.0	10.5	11.7	0.20	0.26	0.29
1,2,3,4,6,7,8-HpCDF	Newark	8.01	0.0020 ± 0.0005*	0.0279 ± 0.0093*	108	0.54	89.0	3.5	6.1	0.09	0.08	0.14
TOTAL HpCDF	Arthur	NA	0.0017 ± 0.0007*	0.0510 ± 0.0273#	59	0.76	210.0	5.3	6.7	0.06	0.06	0.07
Total HpCDF	Newark	NA	0.0028 ± 0.0007*	0.0322 ± 0.0113*	93	0.59	130.0	6.7	10.7	0.11	0.10	0.16
OCDF	Arthur	8.60	0.0008 ± 0.0003	0.0215 ± 0.0131 P = 0.1173	140	0.45	200.0	3.4	7.1	0.08	0.04	0.08
OCDF	Newark	8.60	0.0011 ± 0.0003*	0.0190 ± 0.0078*	158	0.41	210.0	5.0	11.6	0.05	0.05	0.11

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

Table C4. Modeled output for *Macoma nasuta* exposed to polycyclic aromatic hydrocarbons (PAHs).

Chemical	Sediment	Log K_{ow}	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed} (µg/kg)	C_{28} (µg/kg)	Kinetic C_{SS} (µg/kg)	Measured $BSAF_{28d}$	Modeled $BSAF_{28d}$	Modeled $BSAF_{SS}$
FLA	Arthur	4.22	0.0306 ± 0.0068*	0.0938 ± 0.0235*	32	0.93	103.0	31.2	31.9	0.61	0.68	0.69
FLA	Newark	4.22	0.0101 ± 0.0027*	0.1657 ± 0.0469*	18	0.99	1640.0	99.0	95.0	0.16	0.12	0.11
Pyrene	Arthur	5.07	0.0020 ± 0.0003*	0.0418 ± 0.0085*	72	0.69	2190.0	72.3	99.6	0.08	0.07	0.10
Pyrene	Newark	5.07	0.0182 ± 0.0039*	0.1655 ± 0.0378*	18	0.99	1230.0	133.9	128.5	0.24	0.22	0.21
Chrysene	Arthur	5.77	0.0009 ± 0.0002*	0.0229 ± 0.0084*	131	0.47	902.0	16.8	33.7	0.05	0.04	0.08
Chrysene	Newark	5.77	0.0056 ± 0.0019*	0.0890 ± 0.0323*	34	0.92	775.0	44.7	46.3	0.14	0.11	0.12
Benzo[a] anthracene	Newark	5.91	0.0059 ± 0.0017*	0.1144 ± 0.0354*	26	0.96	646.0	32.0	31.7	0.11	0.10	0.10
Benzo[b] fluranthene	Arthur	5.80	0.0006 ± 0.0002*	0.0319 ± 0.0145*	94	0.59	1360.0	15.1	24.3	0.03	0.02	0.04
Benzo[b] fluranthene	Newark	5.80	0.0094 ± 0.0045#	0.1643 ± 0.0841#	18	0.99	435.0	24.6	23.6	0.09	0.11	0.11
Benzo[k] fluoranthene	Newark	6.00	0.0077 ± 0.0019*	0.2143 ± 0.0543*	14	1.00	413.0	14.87	14.1	0.07	0.07	0.07
Benzo[a] pyrene	Newark	6.04	0.0044 ± 0.0012*	0.1410 ± 0.0417*	21	0.98	550.0	16.8	16.3	0.06	0.06	0.06

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

& Significance ($p < 0.20$): the elimination rate was fast and could not be more accurately documented without time points < 3 days

k_s = chemical uptake rate constant (g sediment / g tissue * day)

k_e = chemical elimination rate constant (1/day)

$TSS_{95\%}$ = time to steady state

f_{ss} = fraction of steady state at 28 days

C_{sed} = concentration in the sediment

C_{28} = concentration in tissue after 28 days of exposure

C_{SS} = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

Table C5. Modeled output for *Macoma nasuta* exposed to mercury (Hg) and methyl mercury (Me-Hg). Results were unavailable in the Newark Bay treatment.

Chemical	Sediment	k_s	k_e	$TSS_{95\%}$ (Days)	28-d f_{ss}	C_{sed}	C_{28}	Kinetic C_{SS}
Hg	Arthur	0.0590 ± 0.0154*	0.0353 ± 0.0123*	85	0.63	0.0468	0.0491	0.0743
Hg	Newark	0.1058 ± 0.0363*	0.0451 ± 0.0190#	67	0.72	0.0255	0.0429	0.0570
Me-Hg	Newark	0.0810 ± 0.0412#	0.1065 ± 0.0593#	28	0.95	2.8	2.0	2.0

* Significance ($p < 0.05$)

Significance ($p < 0.10$)

ks = chemical uptake rate constant (g sediment / g tissue * day)

ke = chemical elimination rate constant (1/day)

TSS95% = time to steady state

fss = fraction of steady state at 28 days

Csed = concentration in the sediment

C28 = concentration in tissue after 28 days of exposure

CSS = concentration in tissue at steady state

BSAF = biota to sediment accumulation factor

NC = Not calculated due to $p > 0.10$

Appendix D: *Nereis virens* Uptake Curves

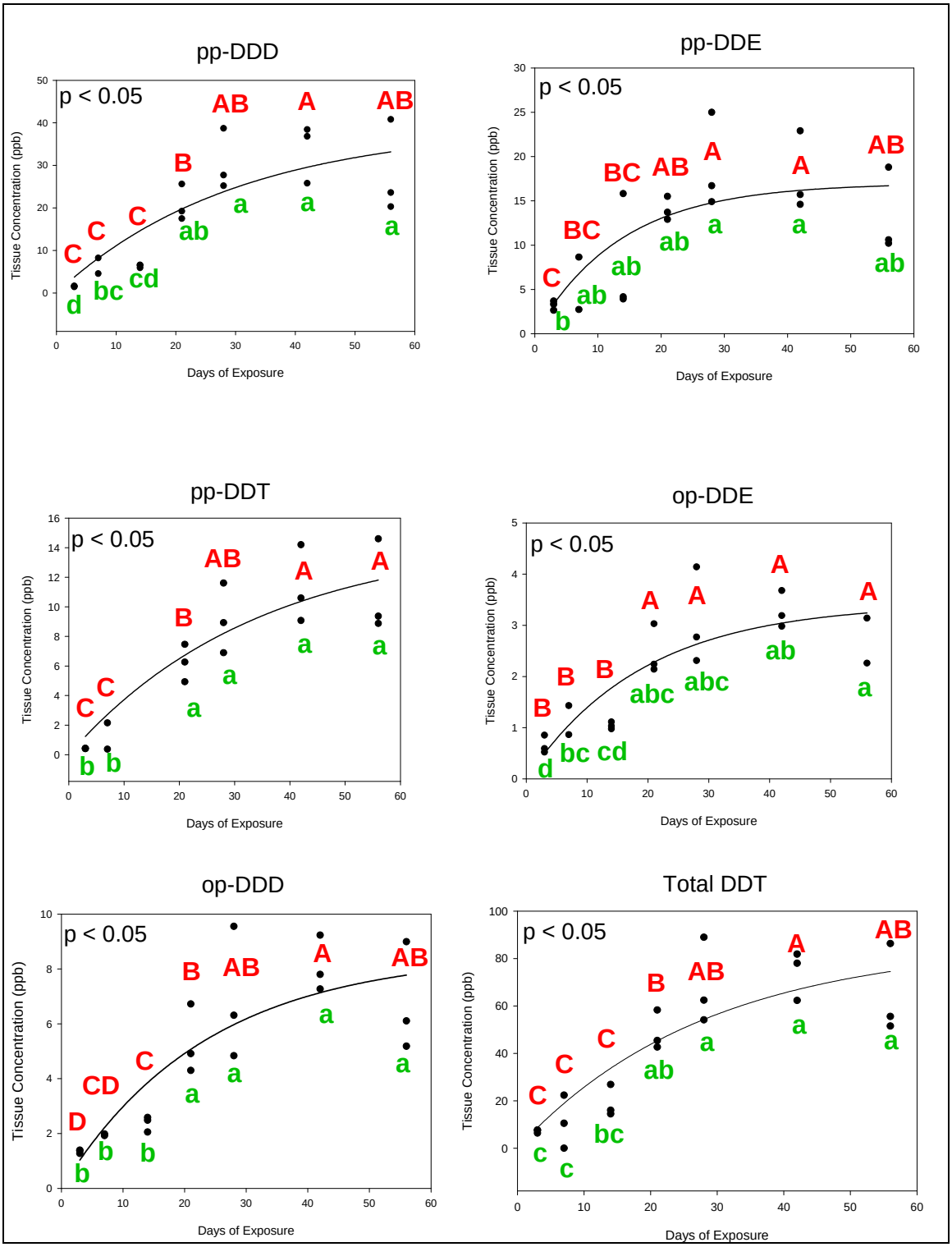

Figure C1. Uptake curves for *Nereis virens* exposed to DDTs in the Arthur Kill sediment. Time points with the same letter designation are not statistically significantly different from one another by Holm-Sidak (red capitals) and Tukey (green lowercase).

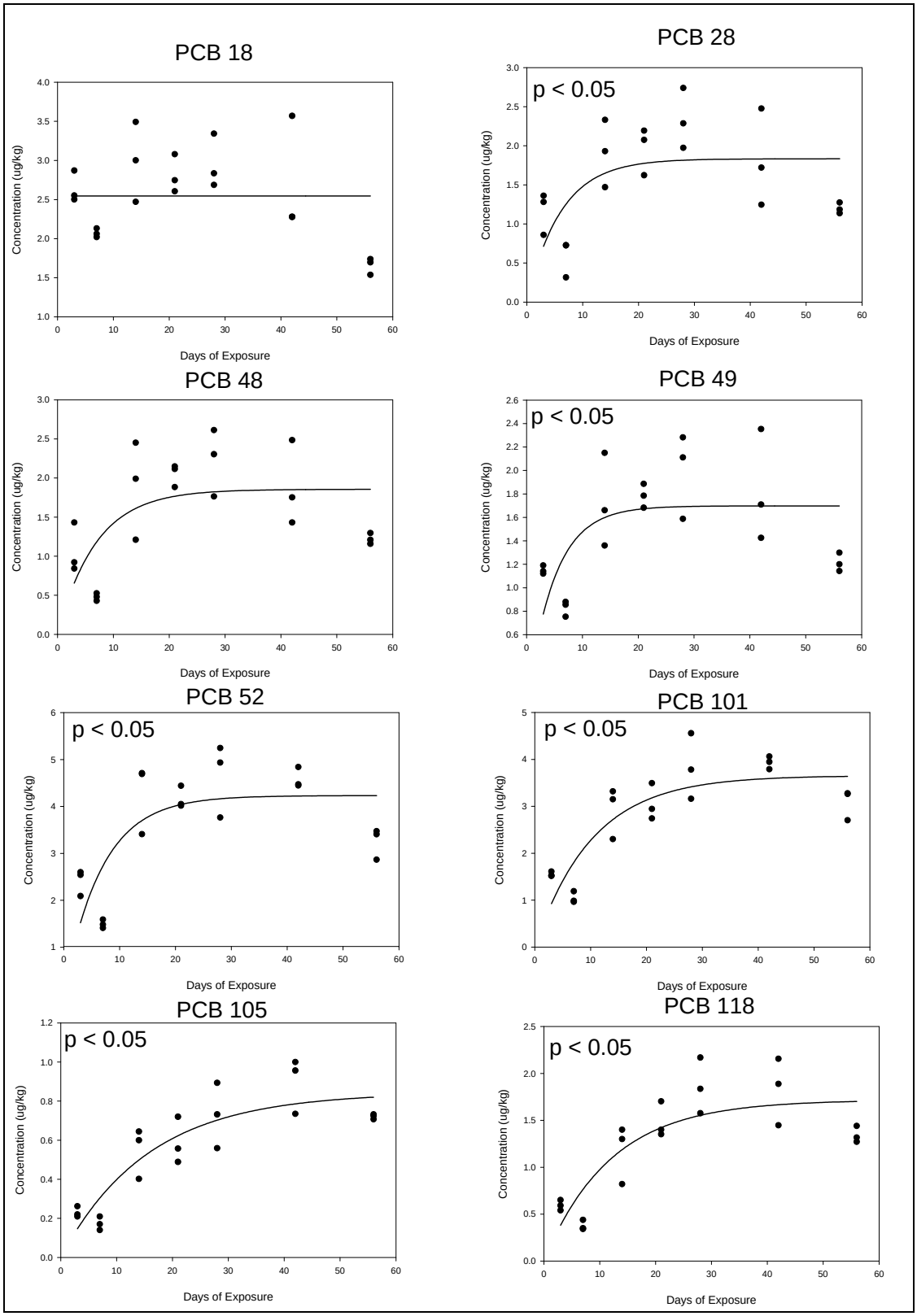

Figure C2. Uptake curves for *Nereis virens* exposed to polychlorinated biphenyls (PCBs) in the Arthur Kill sediment (Continued).

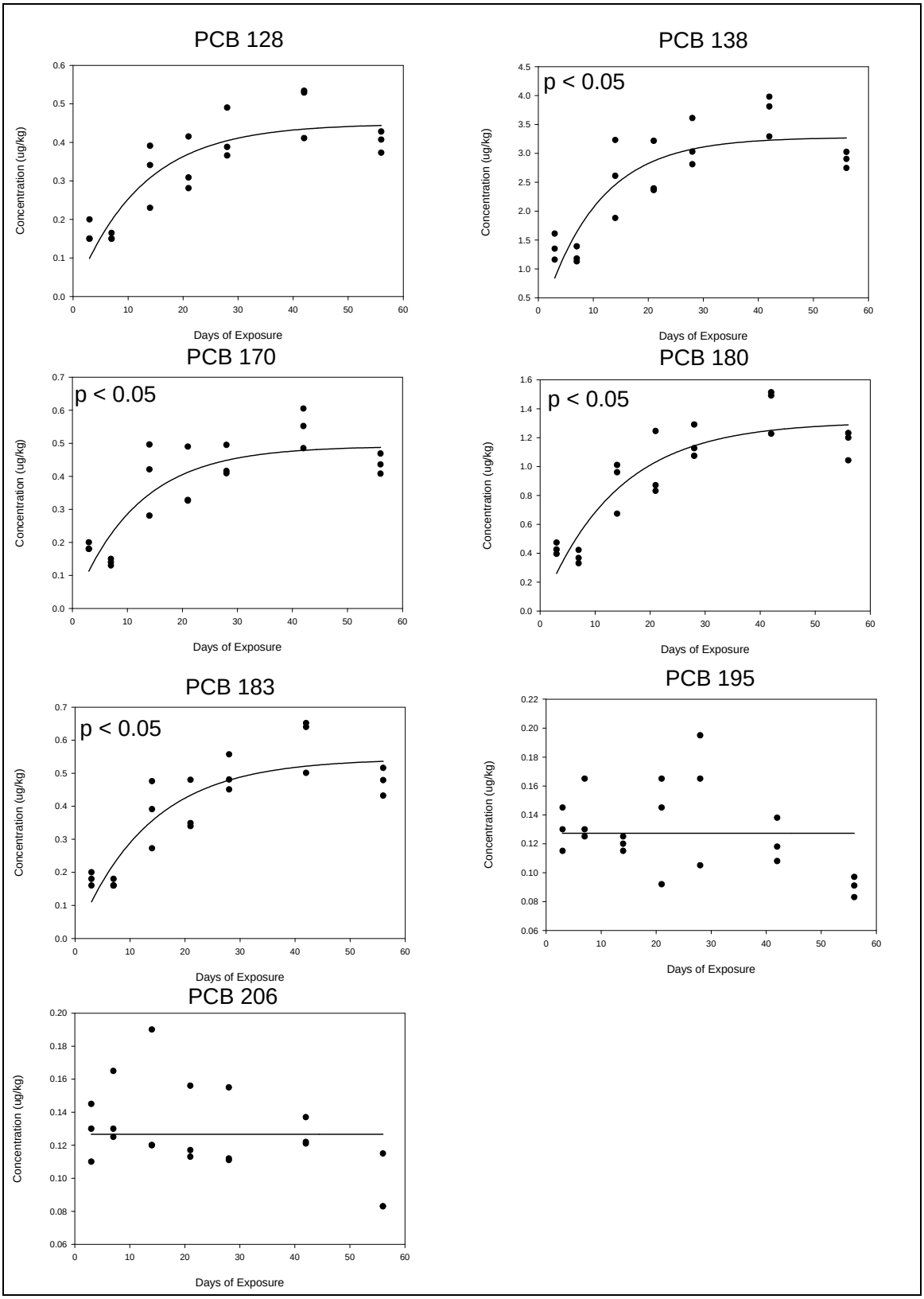

Figure C2. (Concluded).

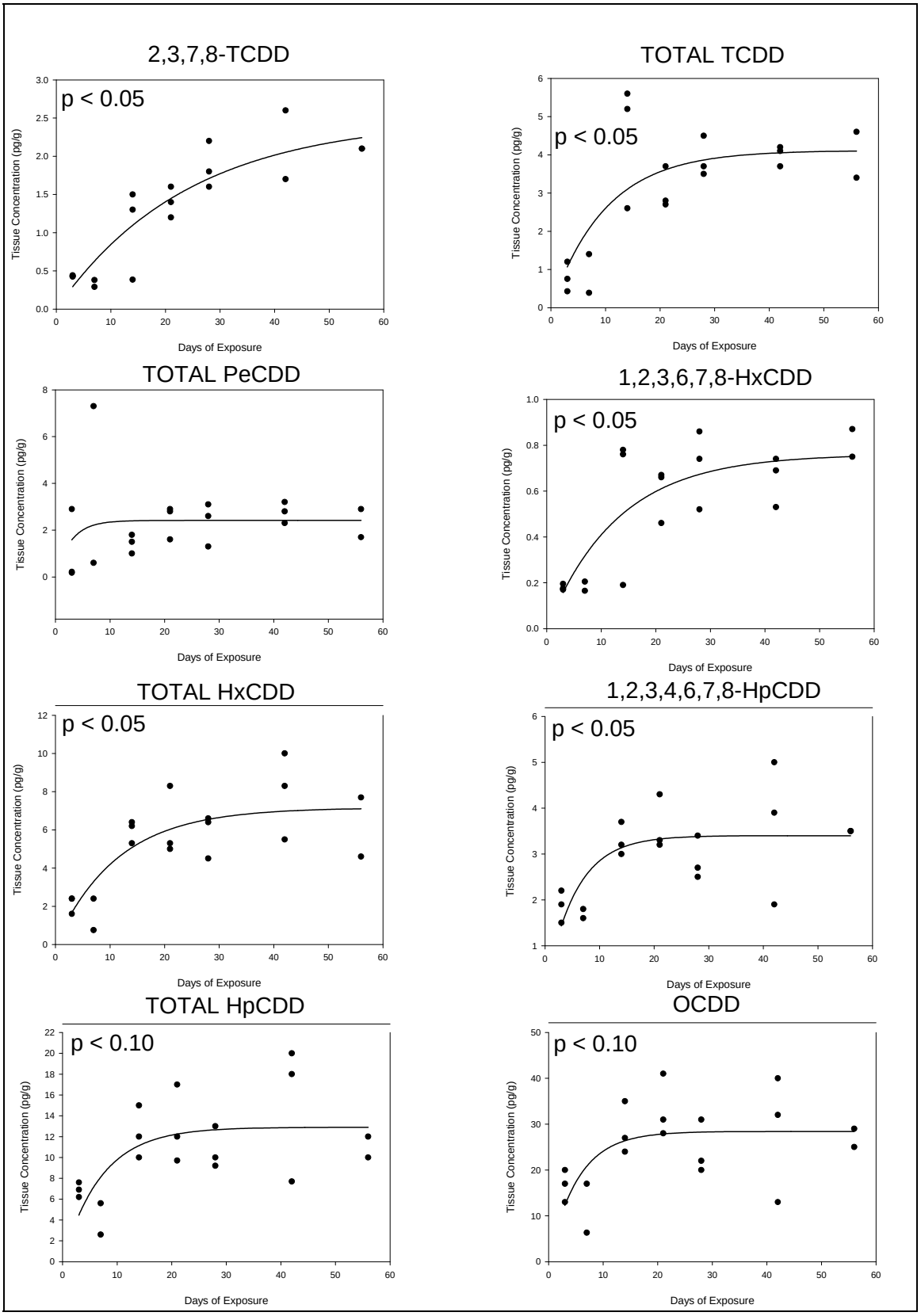

Figure C3. Uptake curves for *Nereis virens* exposed dioxins and furans in the Arthur Kill sediment (Sheet 1 of 3).

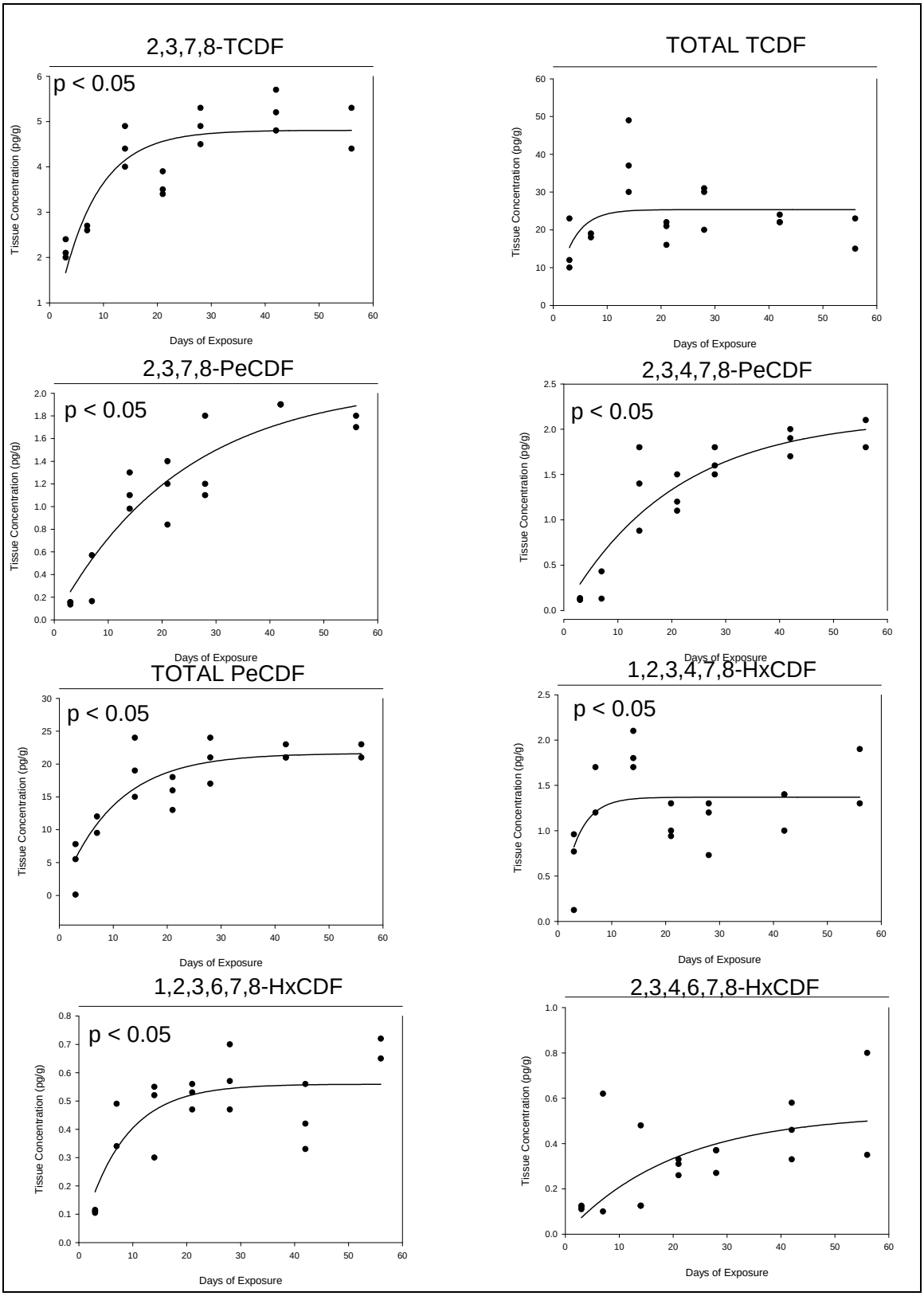

Figure C3. (Sheet 2 of 3).

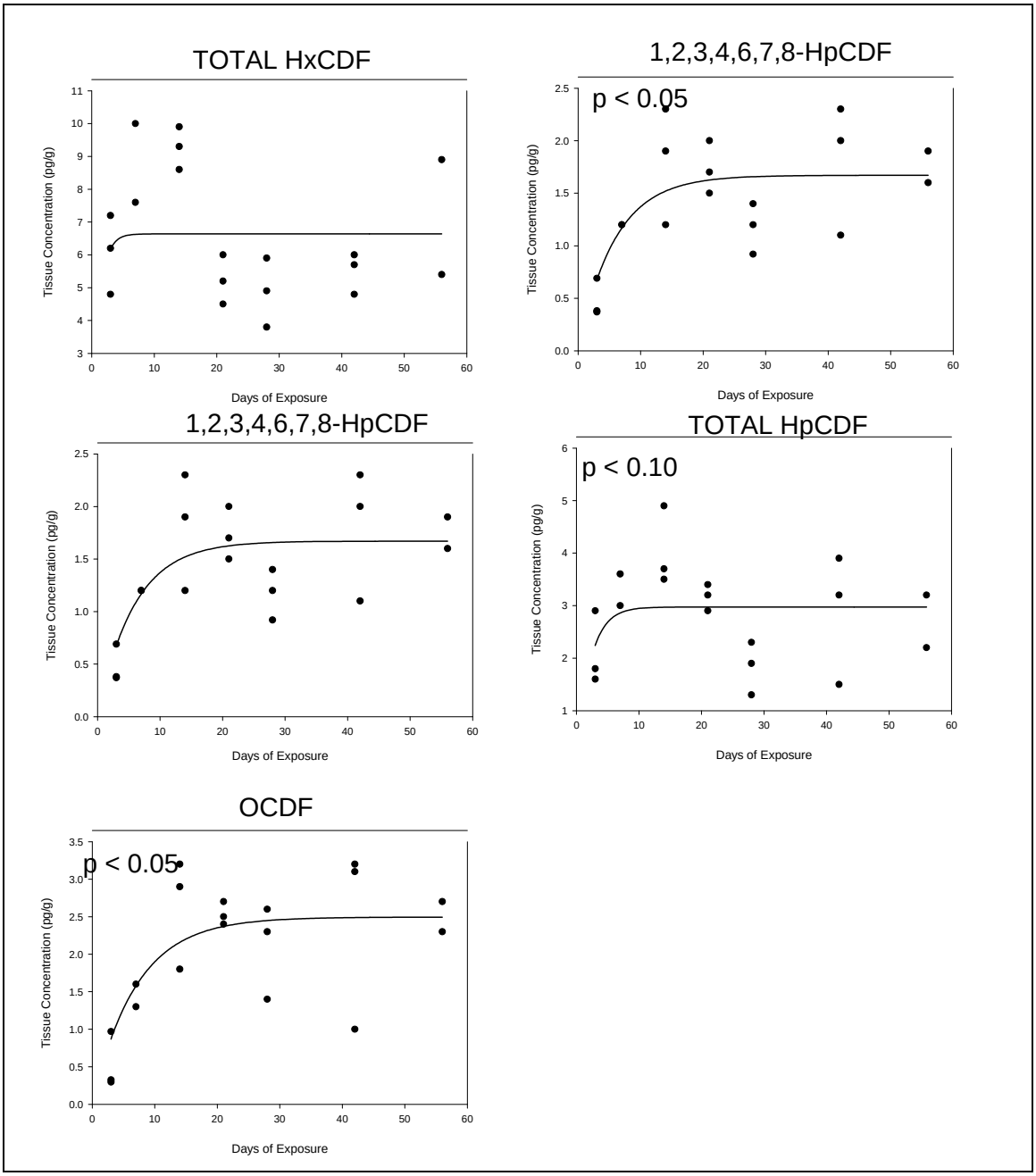

Figure C3. (Sheet 3 of 3).

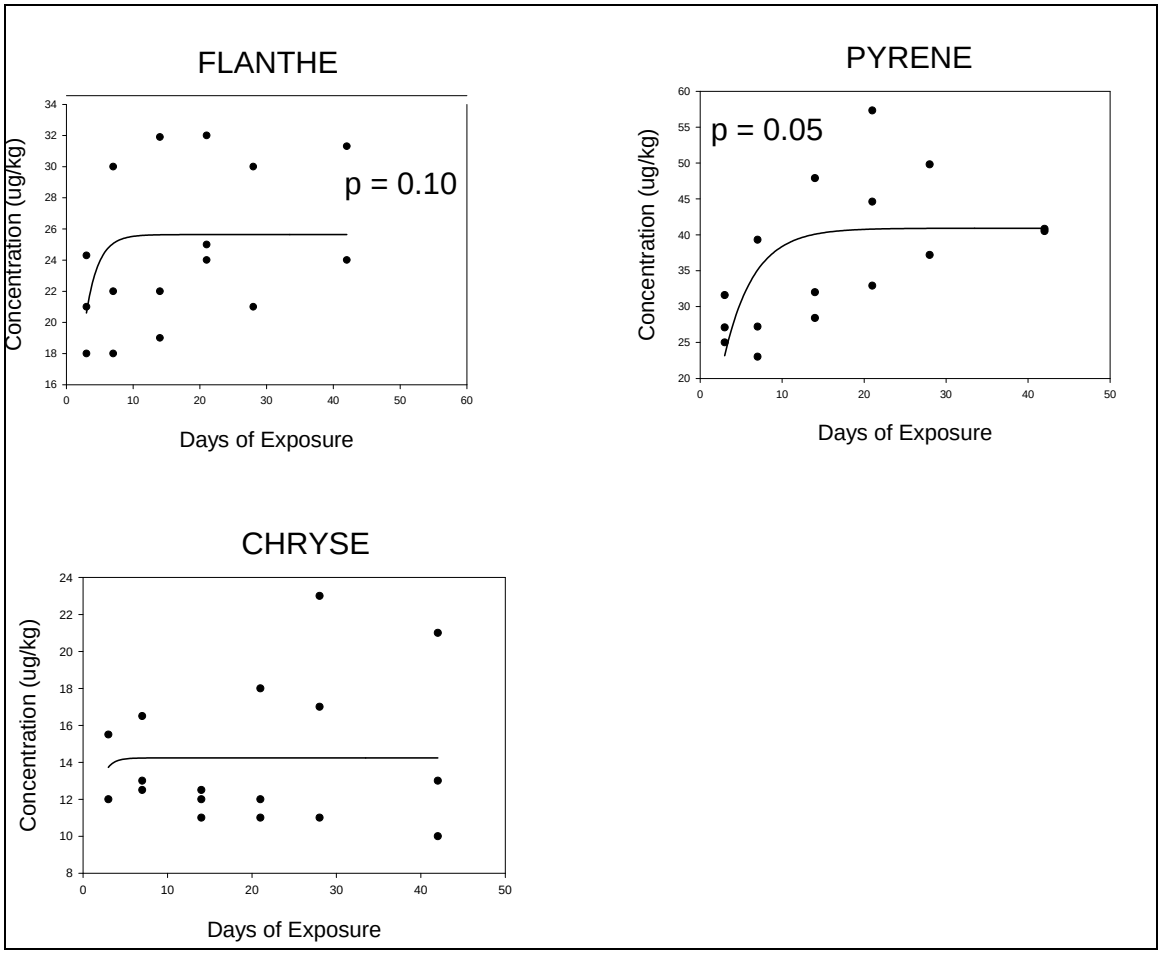

Figure C4. Uptake curves for *Nereis virens* exposed to PAHs in the Arthur Kill sediment.

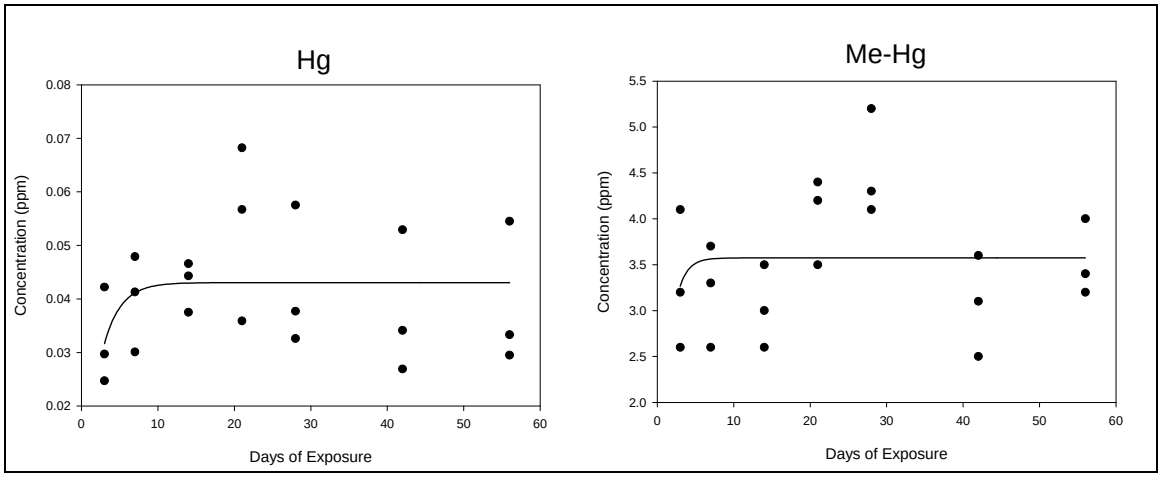

Figure C5. Uptake curves for *Nereis virens* exposed to mercury and methyl mercury in the Arthur Kill sediment.

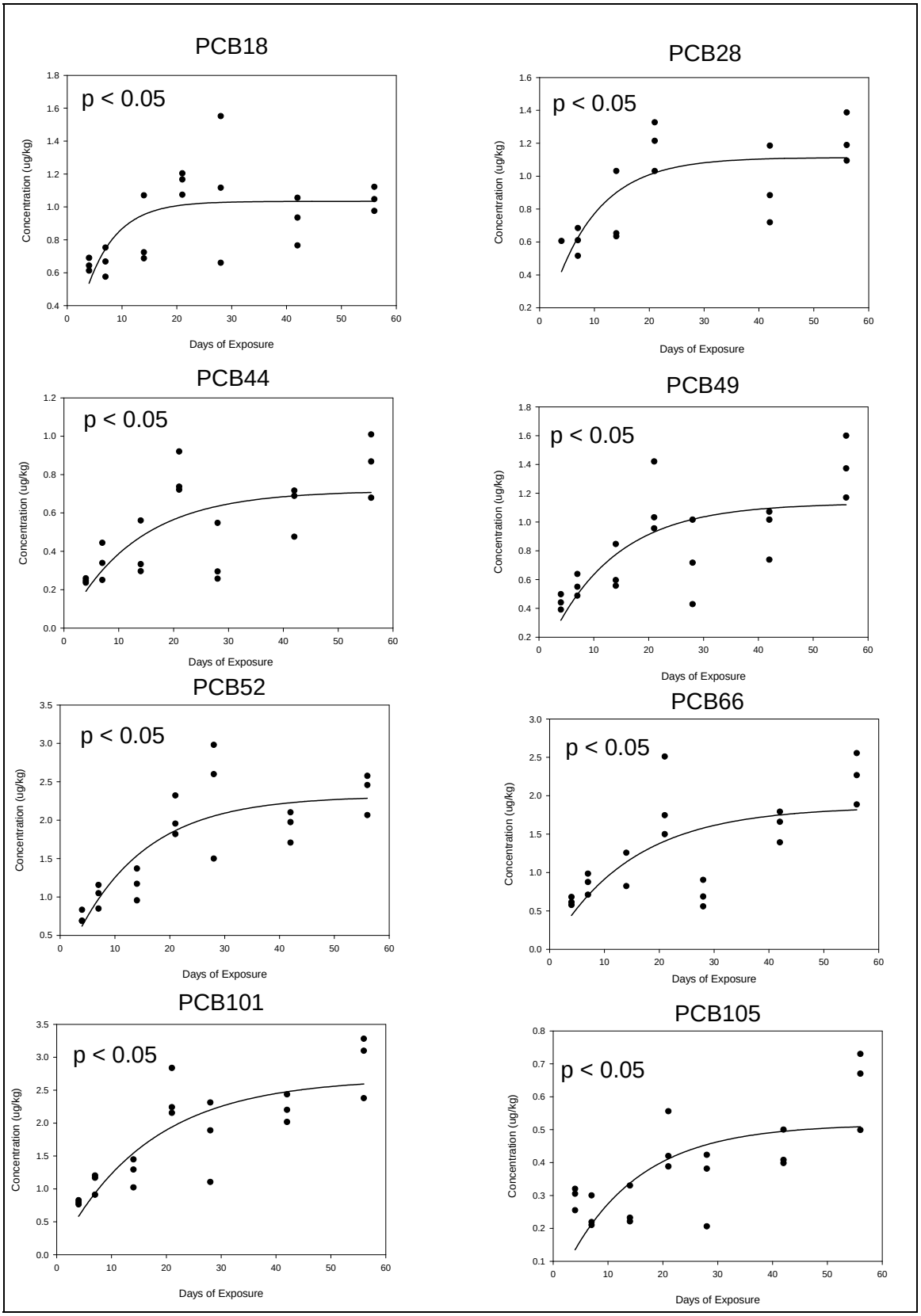

Figure C6. Uptake curves for *Nereis virens* exposed to PCBs in the Newark Bay sediment (Continued).

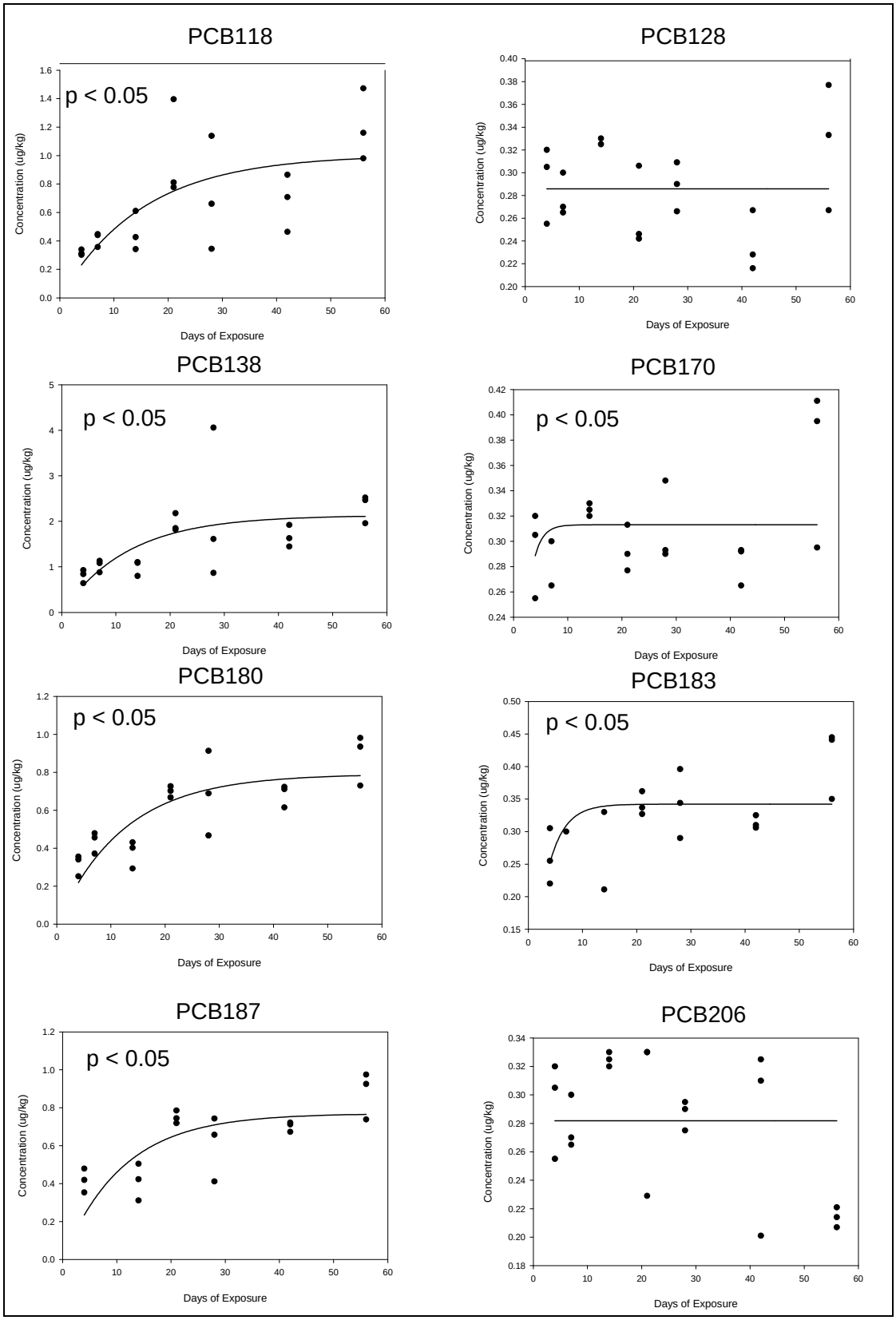

Figure C6. (Concluded).

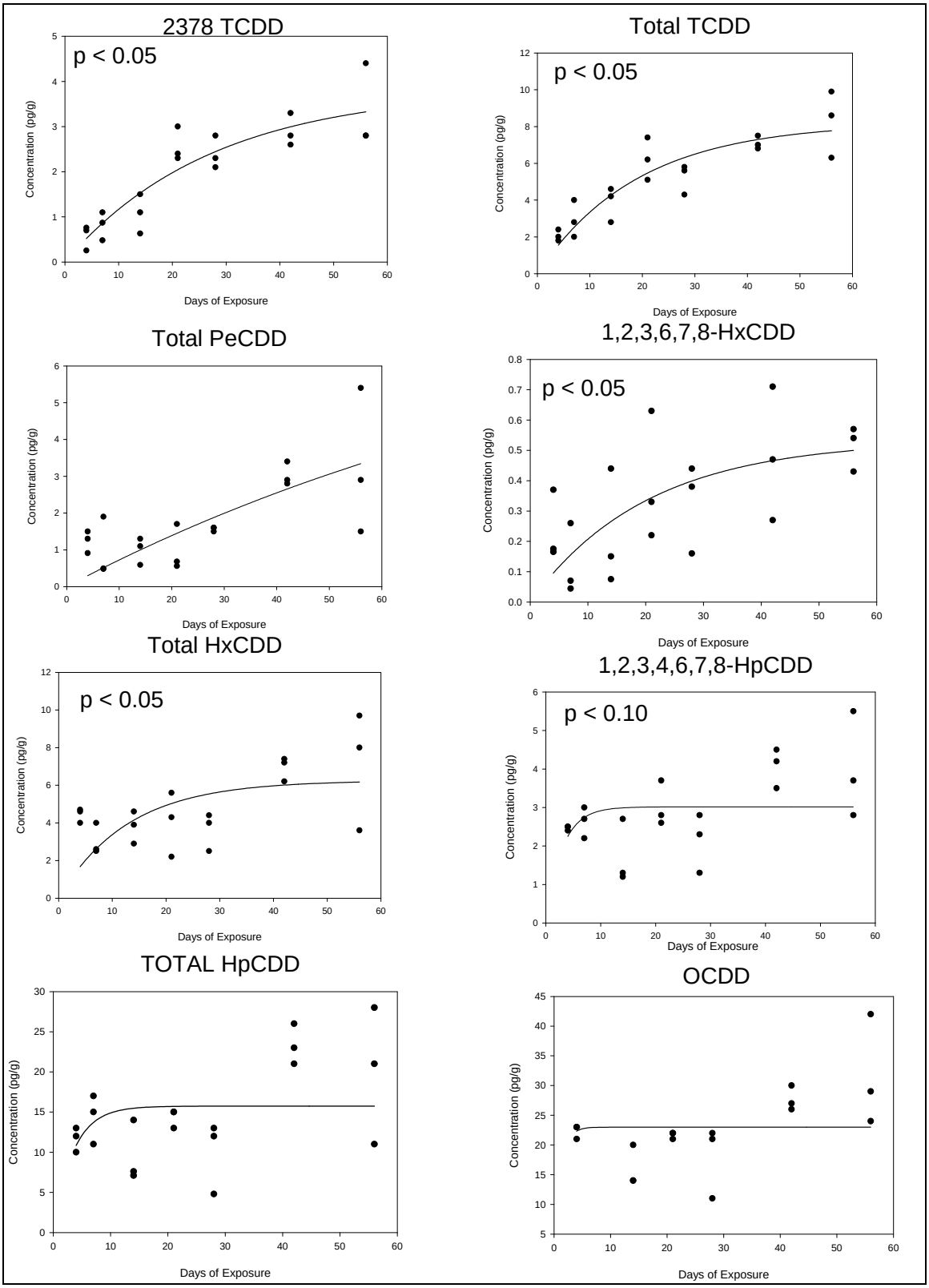

Figure C7. Uptake curves for *Nereis virens* exposed to dioxins and furans in the Newark Bay sediment (Sheet 1 of 3).

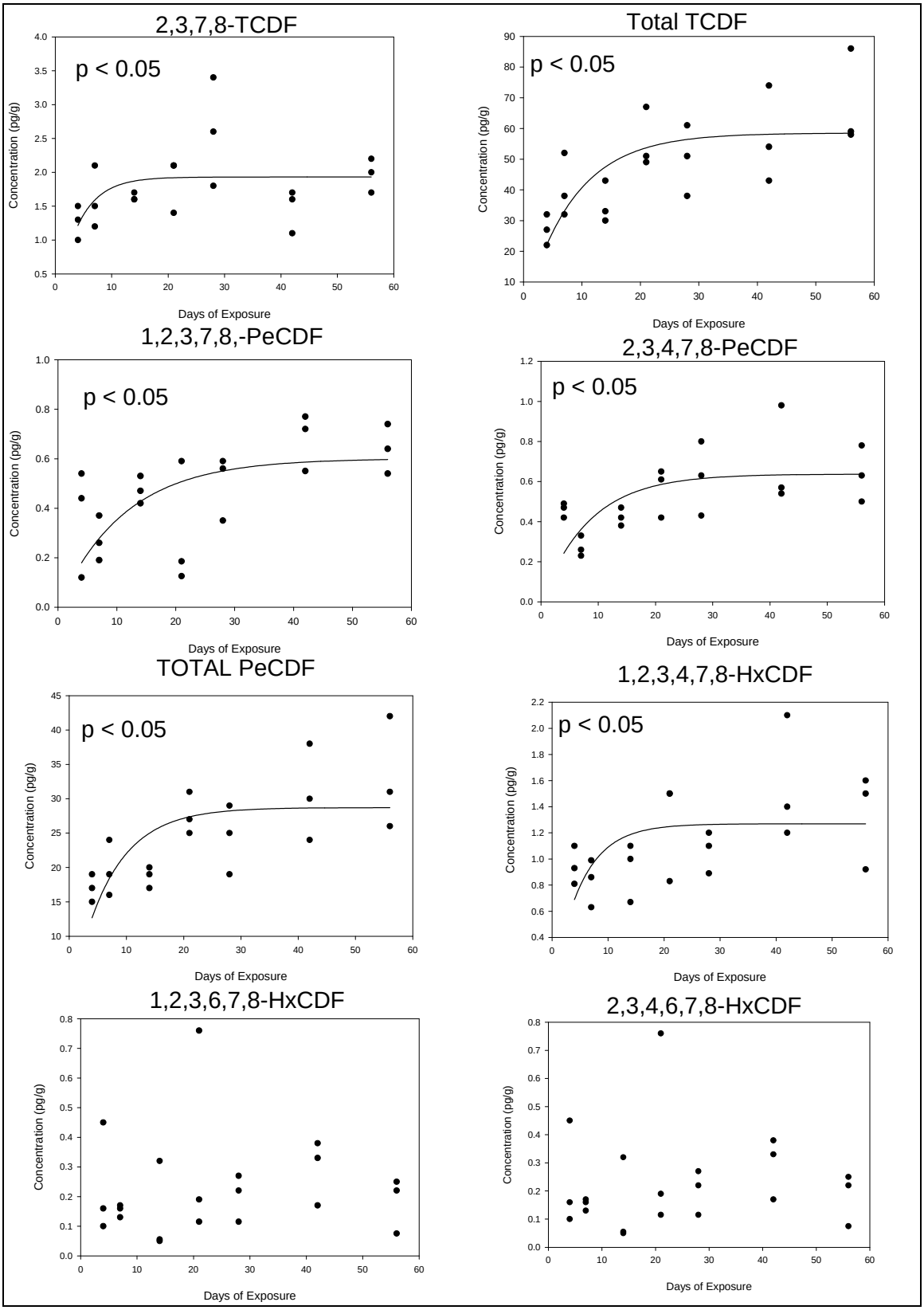

Figure C7. (Sheet 2 of 3).

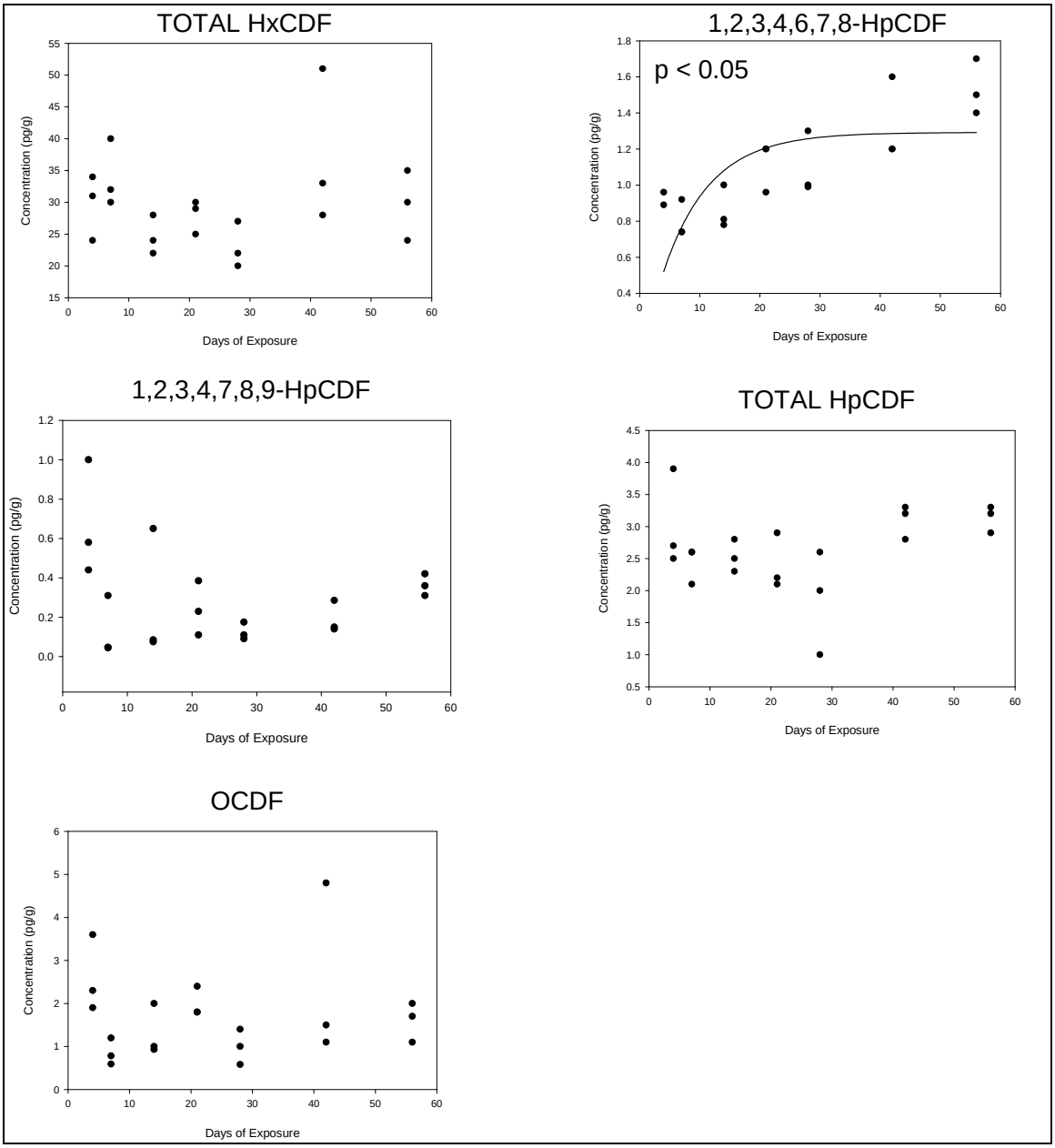

Figure C7. (Sheet 3 of 3).

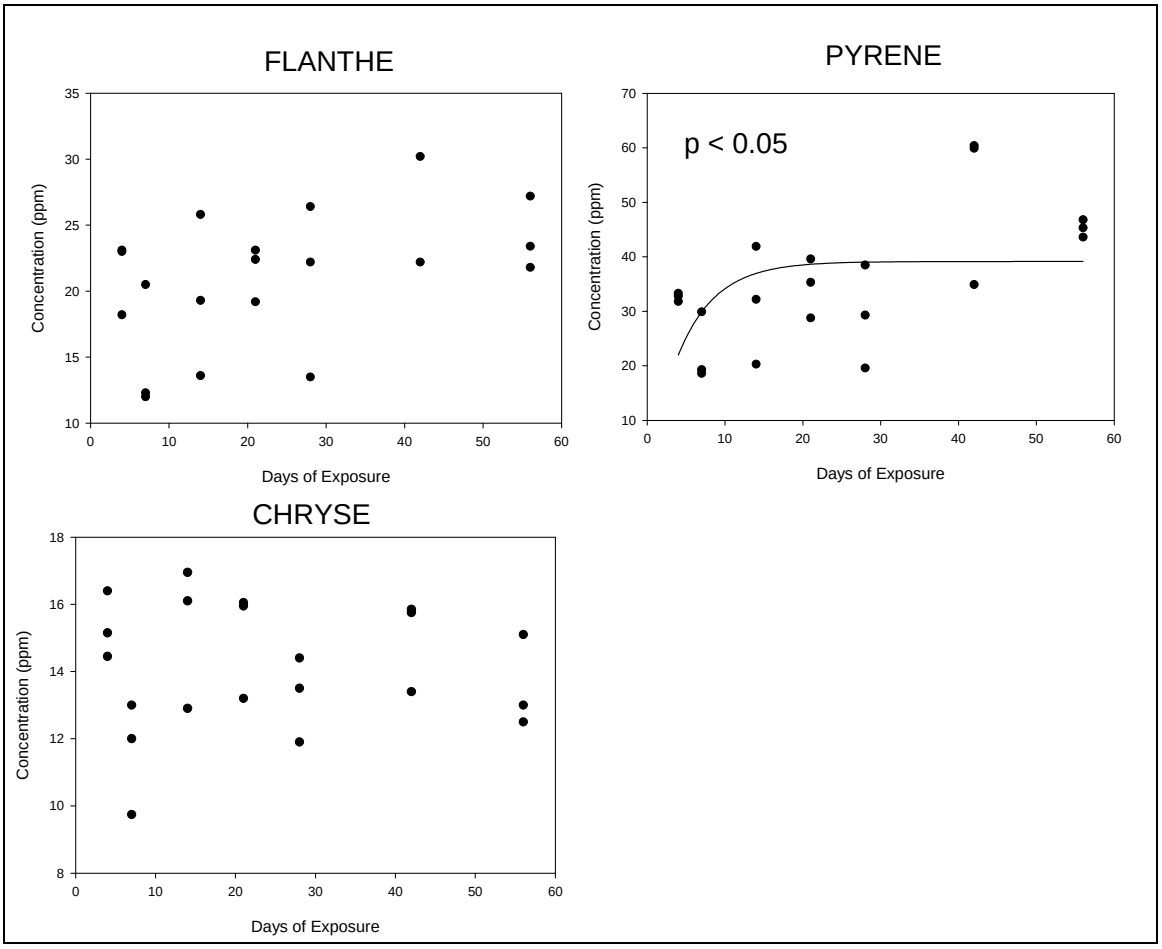

Figure C8. Uptake curves for *Nereis virens* exposed to PAHs in the Newark Bay sediment.

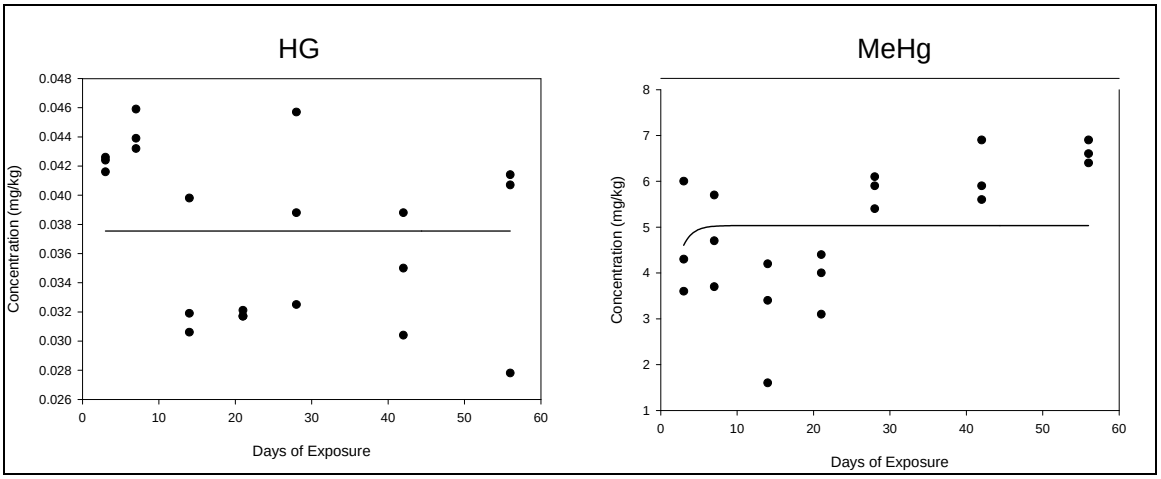

Figure C9. Uptake curves for *Nereis virens* exposed to mercury and methyl mercury in the Newark Bay sediment.

Appendix D: *Macoma nasuta* Uptake Curves

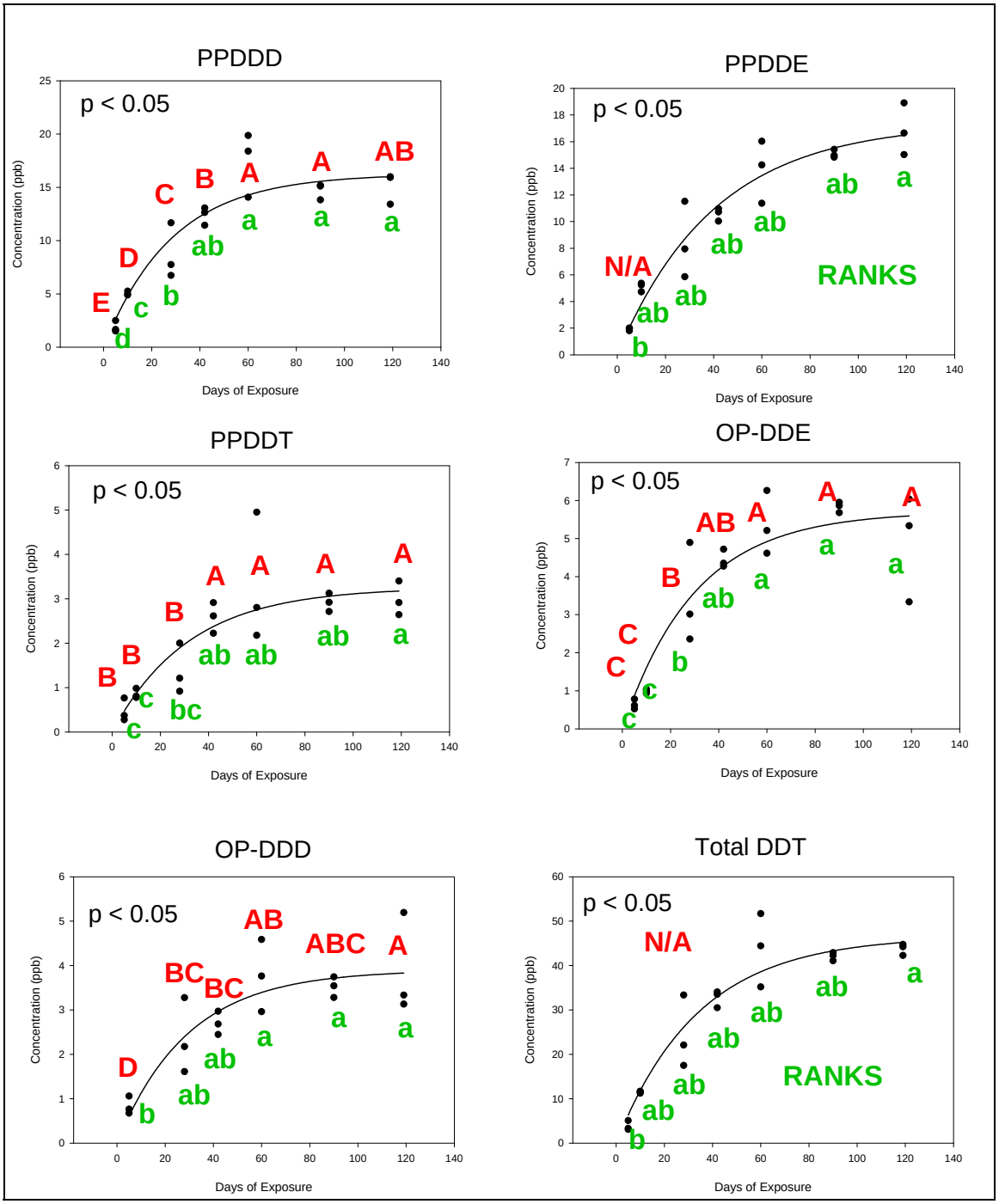

Figure D1. Uptake curves for *Macoma nasuta* exposed to DDTs in the Arthur Kill sediment.

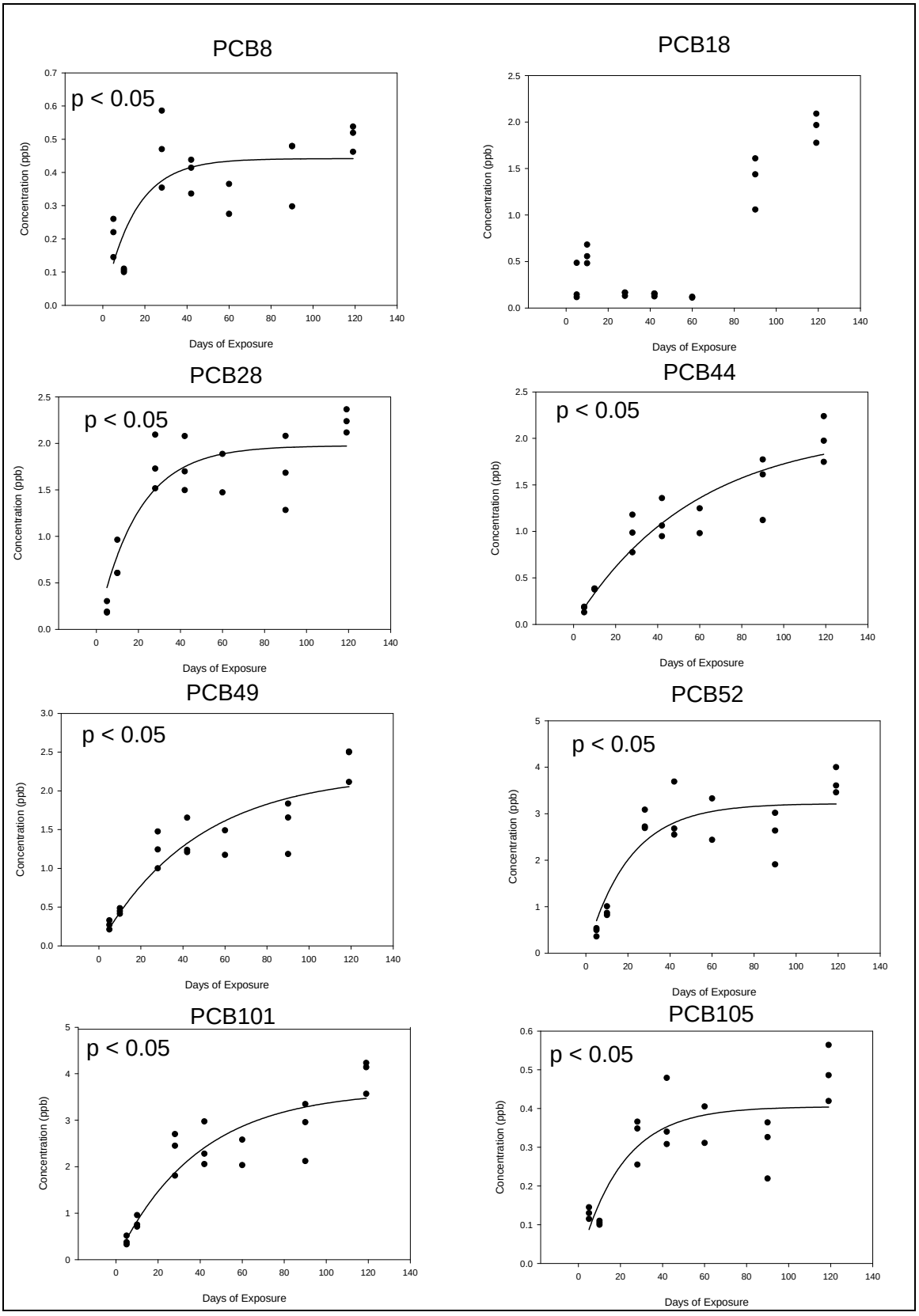

Figure D2. Uptake curves for *Macoma nasuta* exposed to PCBs in the Arthur Kill sediment (Continued).

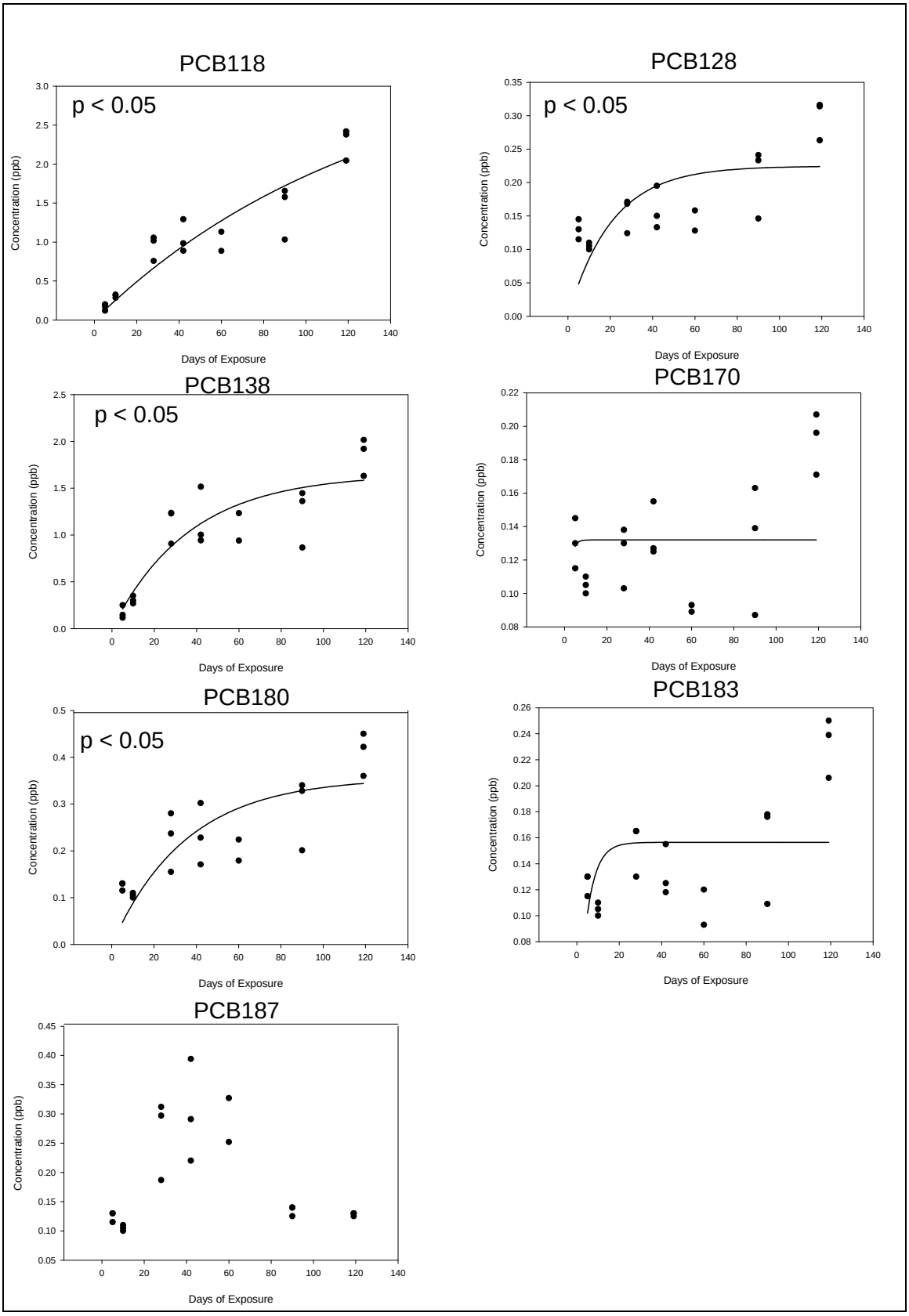

Figure D2. (Concluded).

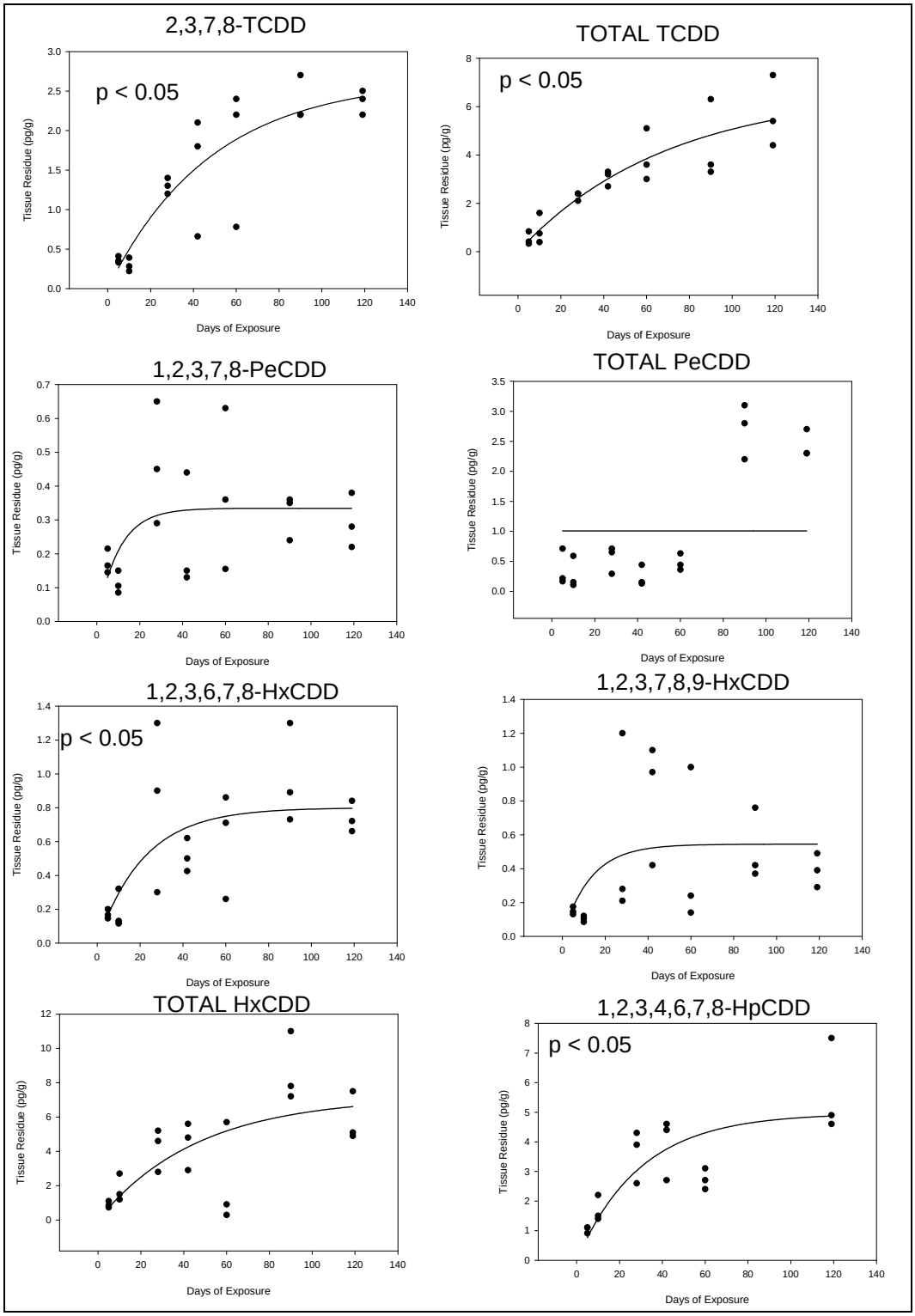

Figure D3. Uptake curves for *Macoma nasuta* exposed to dioxins and furans in the Arthur Kill sediment (Sheet 1 of 3).

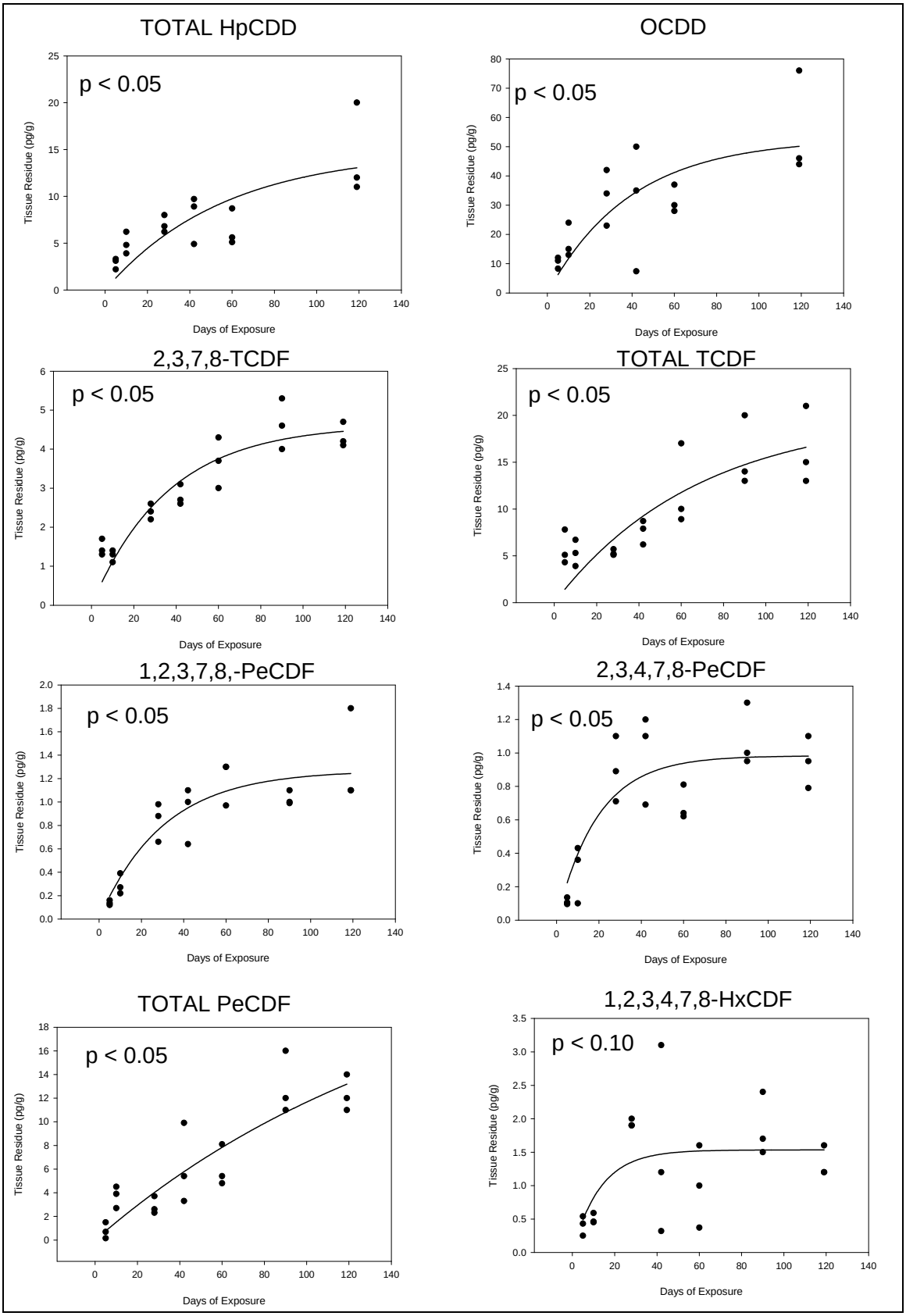

Figure D3. (Sheet 2 of 3).

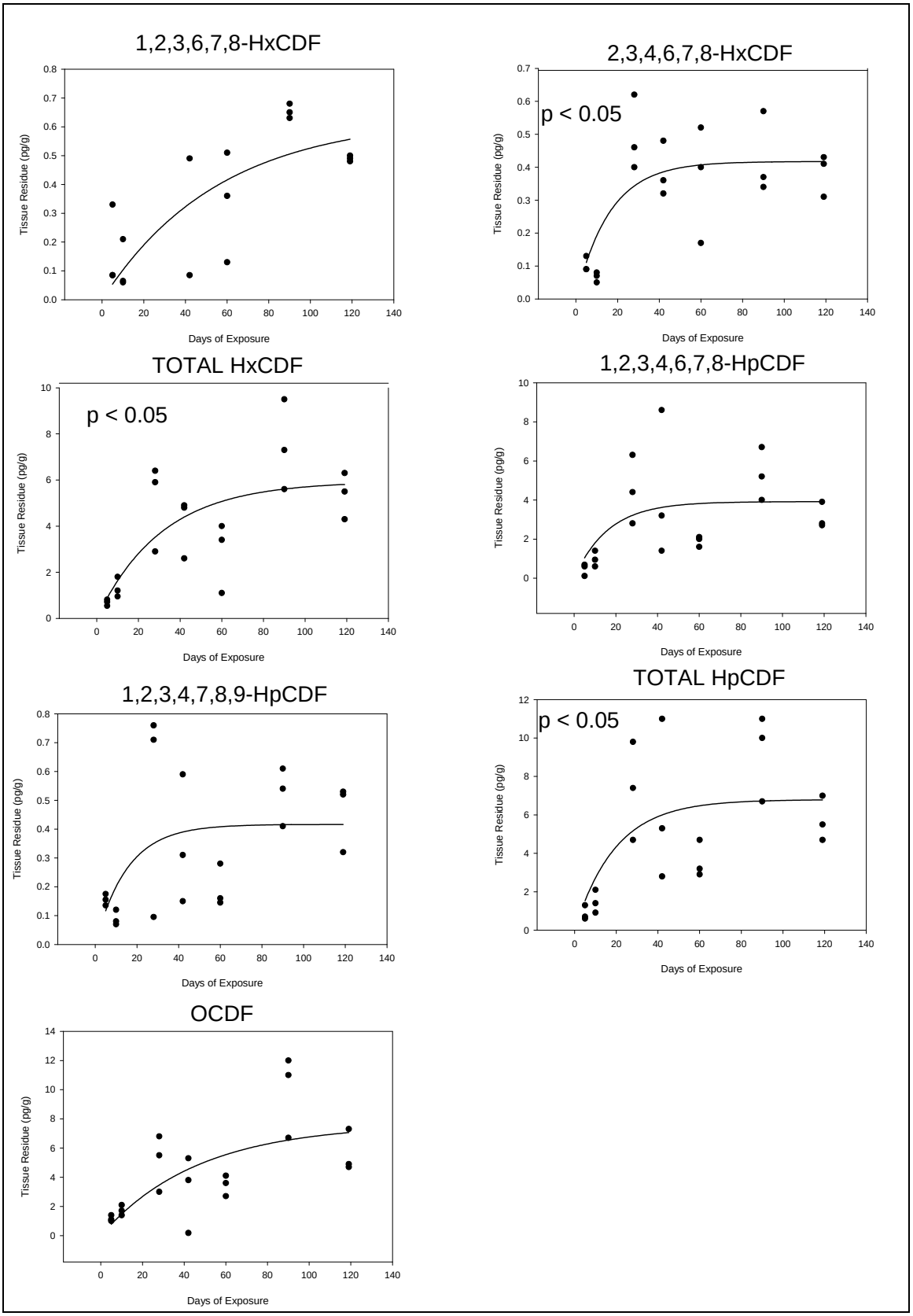

Figure D3. (Sheet 3 of 3).

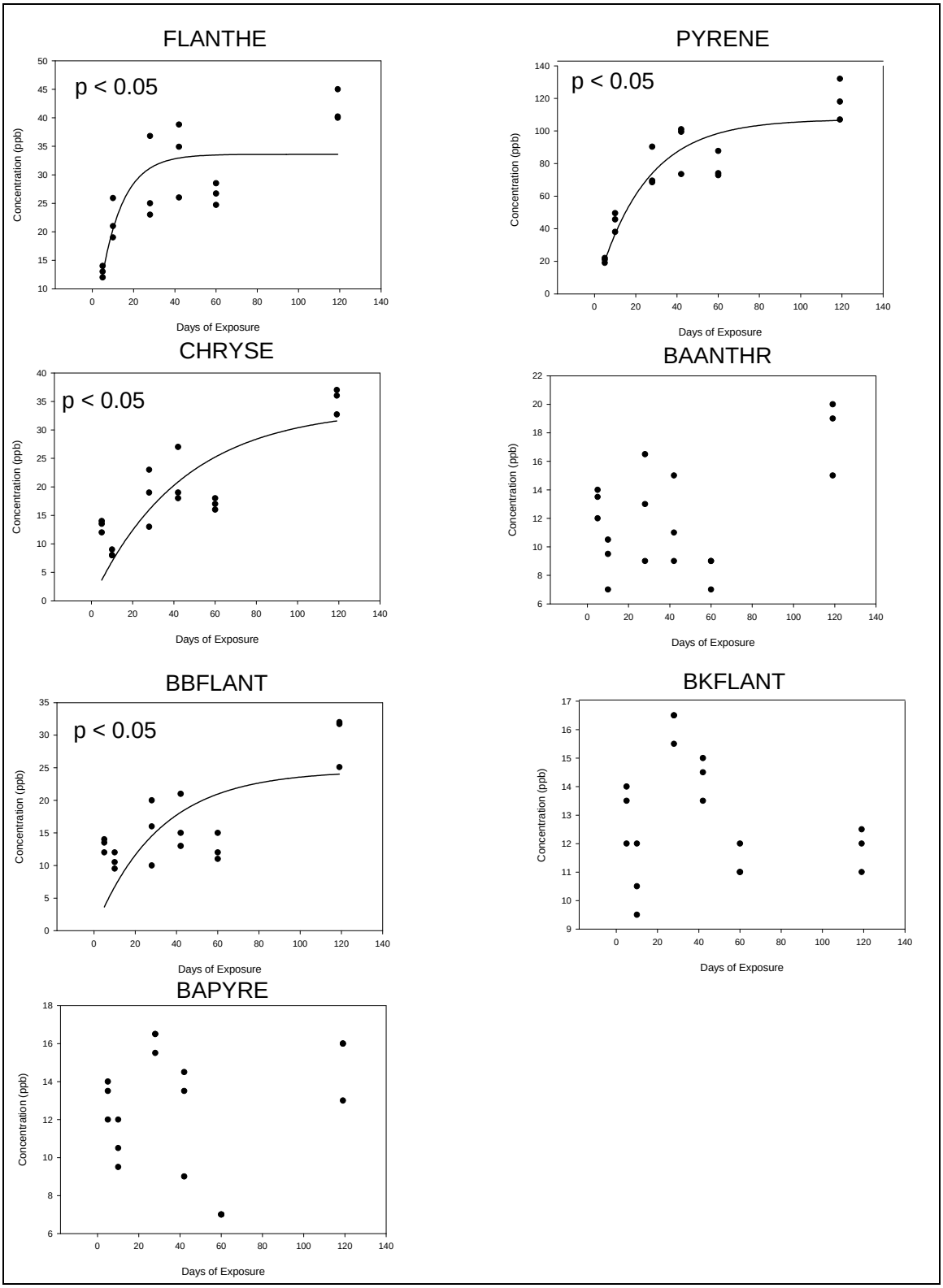

Figure D4. Uptake curves for *Macoma nasuta* exposed to PAHs in the Arthur Kill sediment.

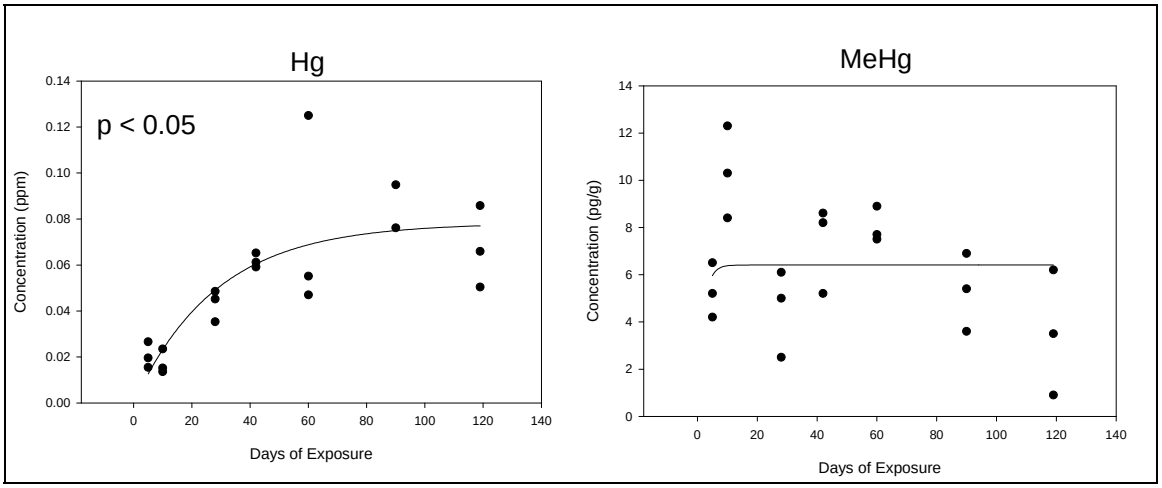

Figure D5. Uptake curves for *Macoma nasuta* exposed to mercury and methyl mercury in the Arthur Kill sediment.

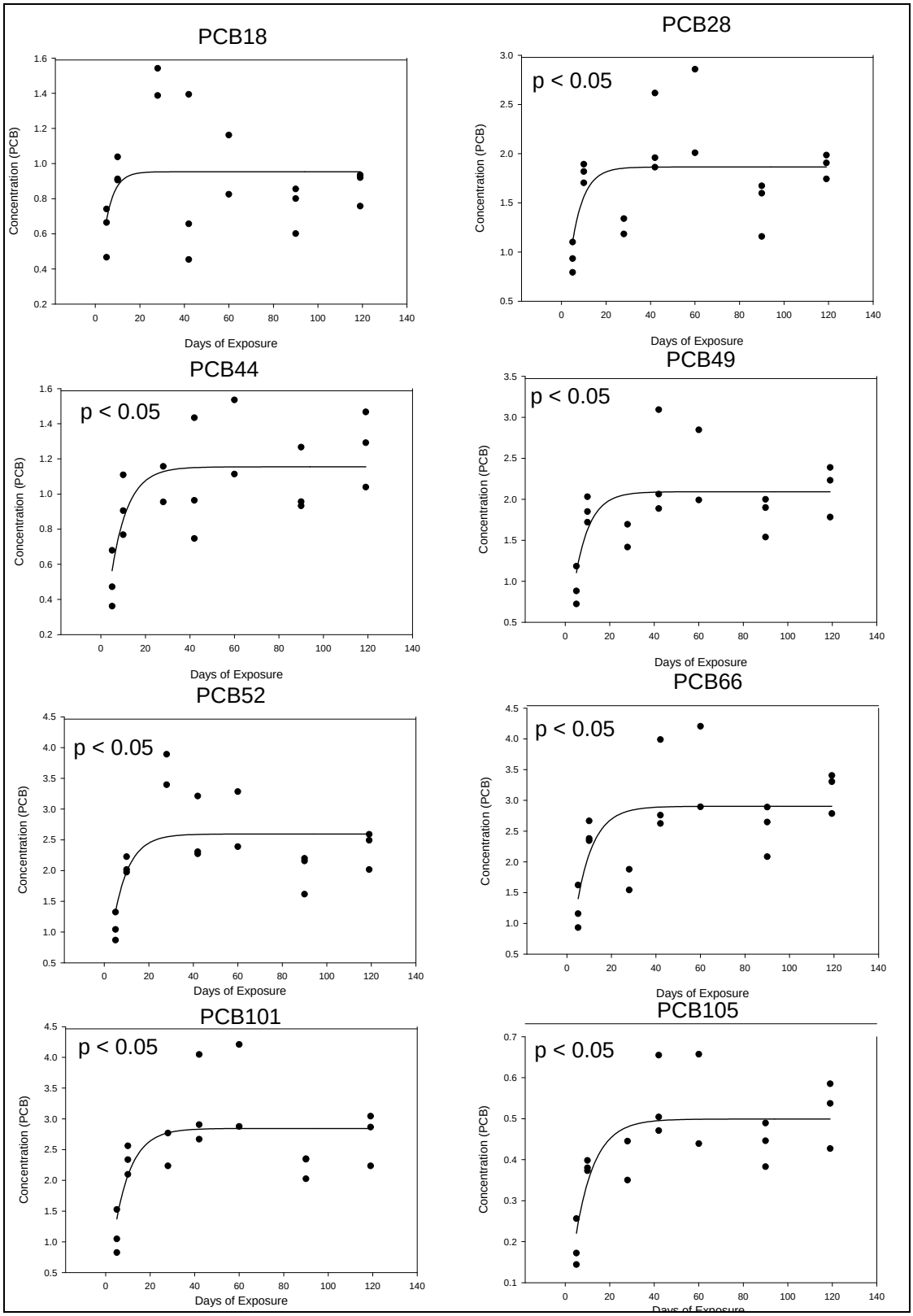

Figure D6. Uptake curves for *Macoma nasuta* exposed to PCBs in the Newark Bay sediment (Continued).

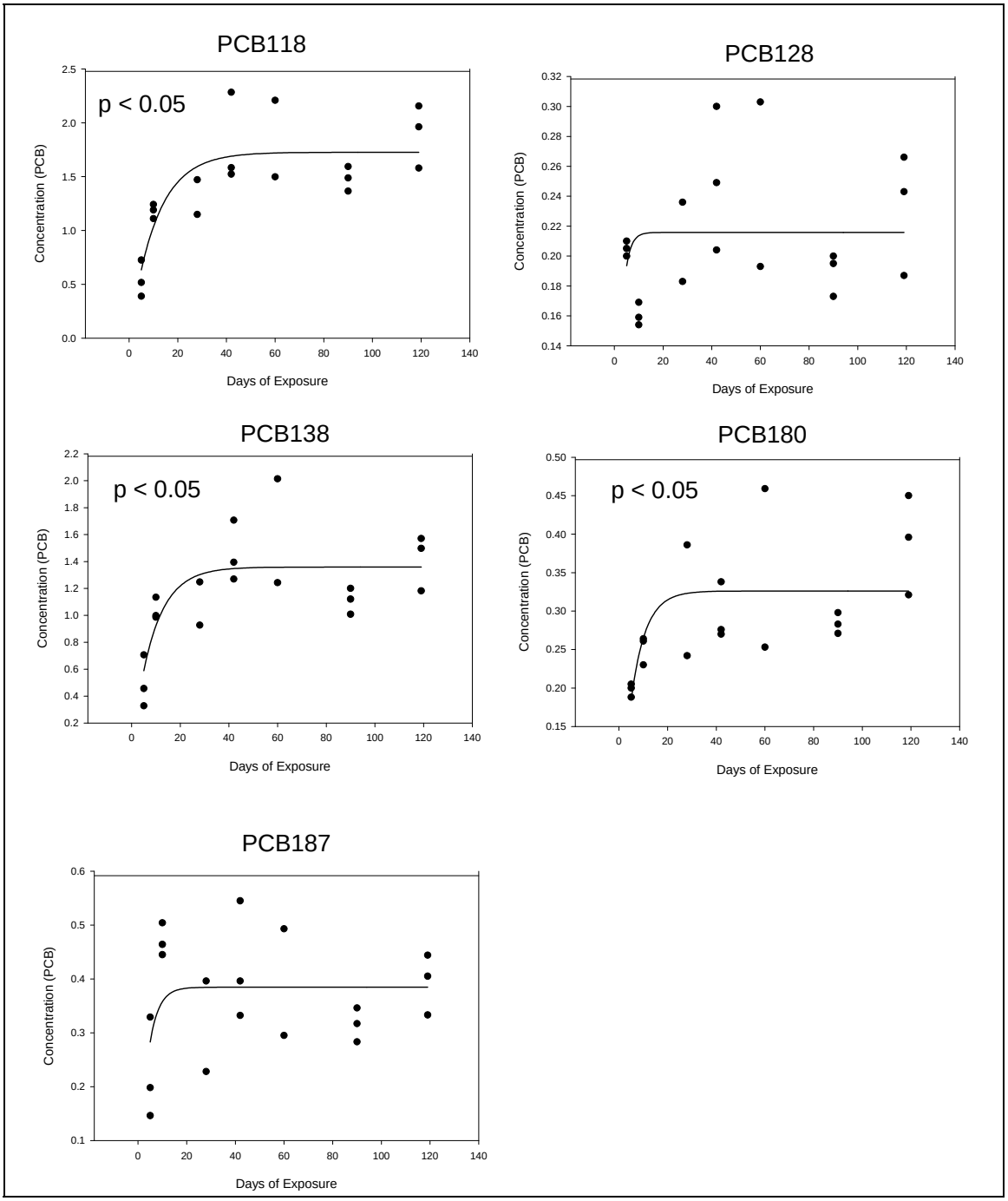

Figure D6. (Concluded).

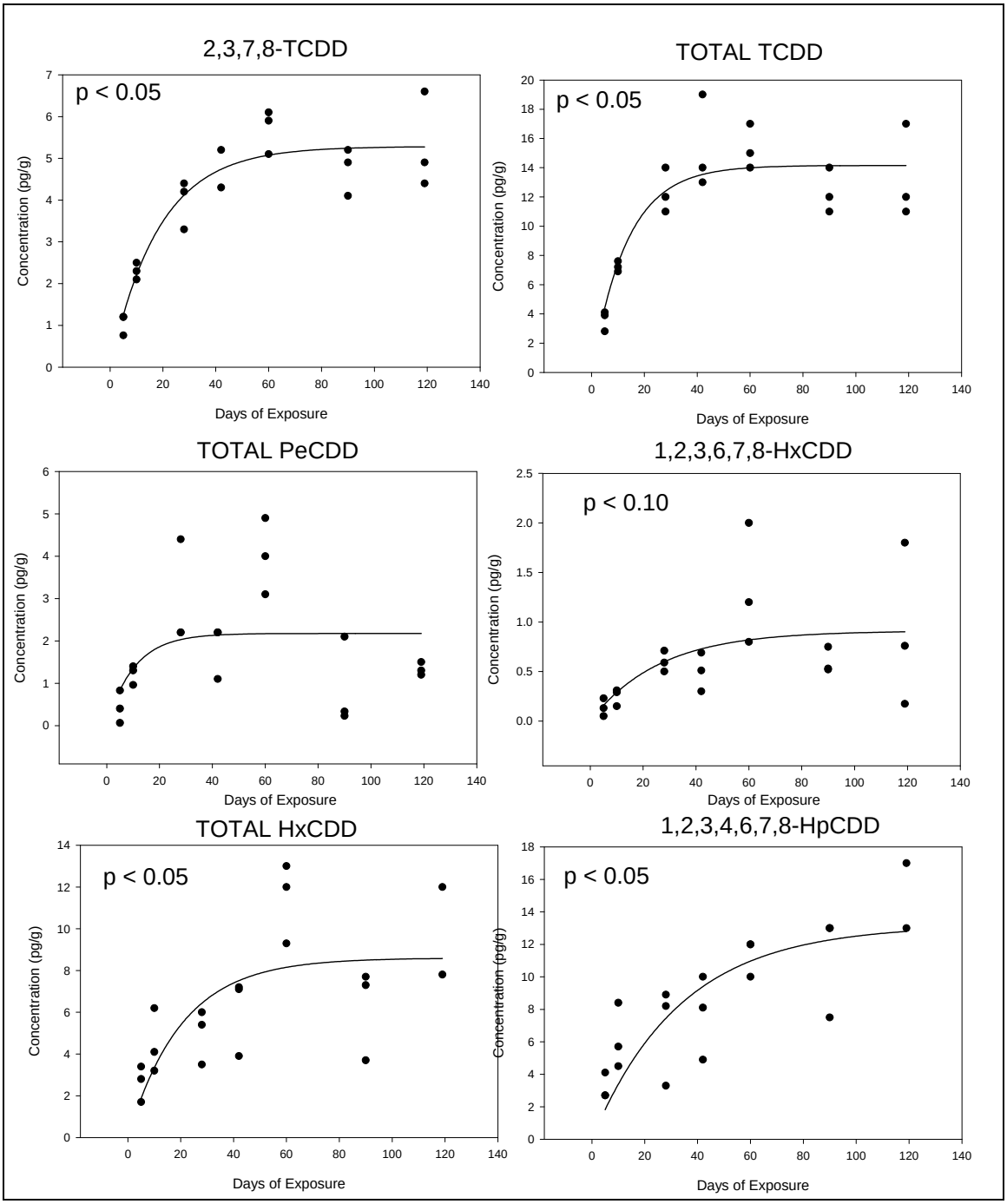

Figure D7. Uptake curves for *Macoma nasuta* exposed to dioxins and furans in the Newark Bay sediment (Sheet 1 of 3).

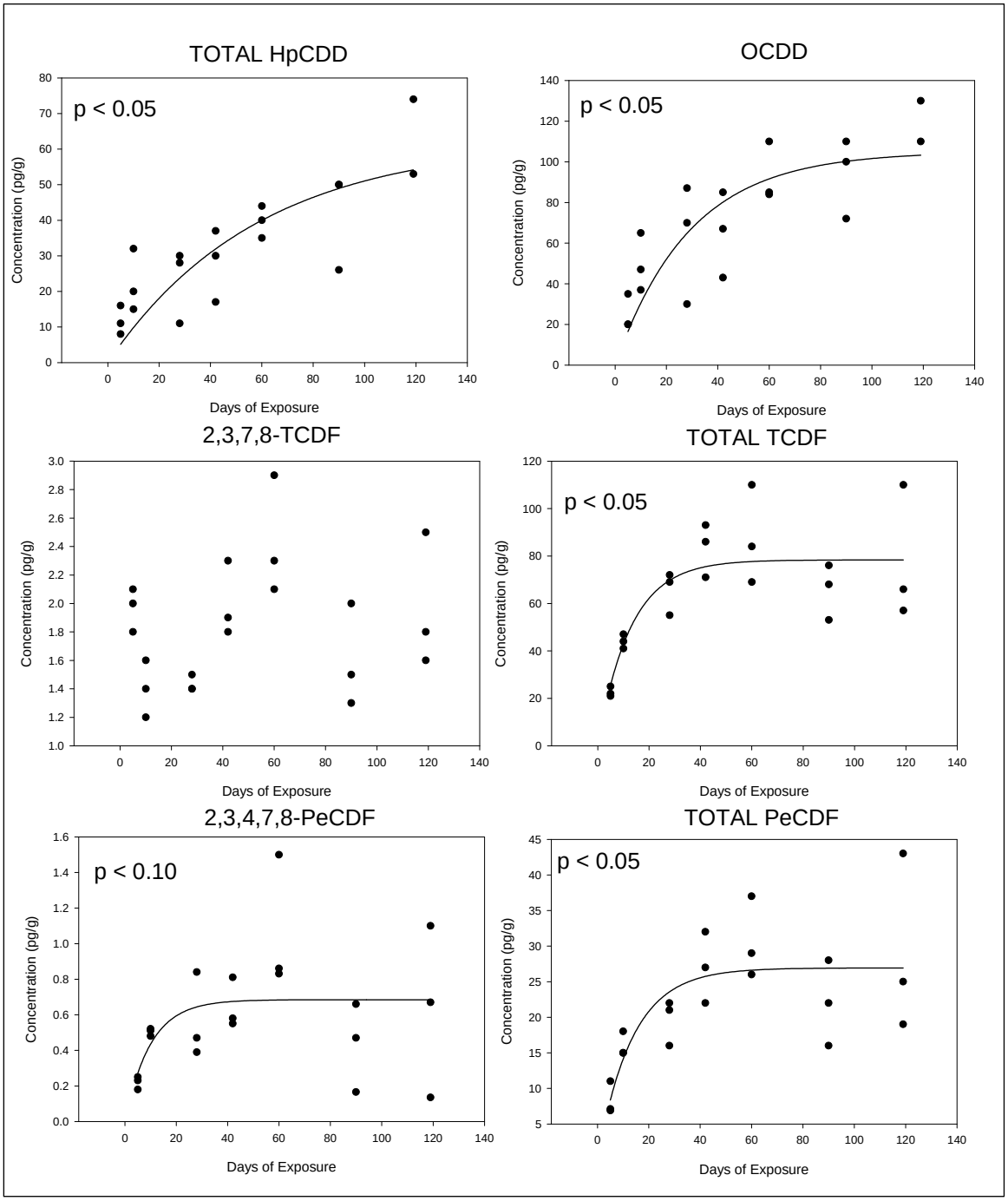

Figure D7. (Sheet 2 of 3).

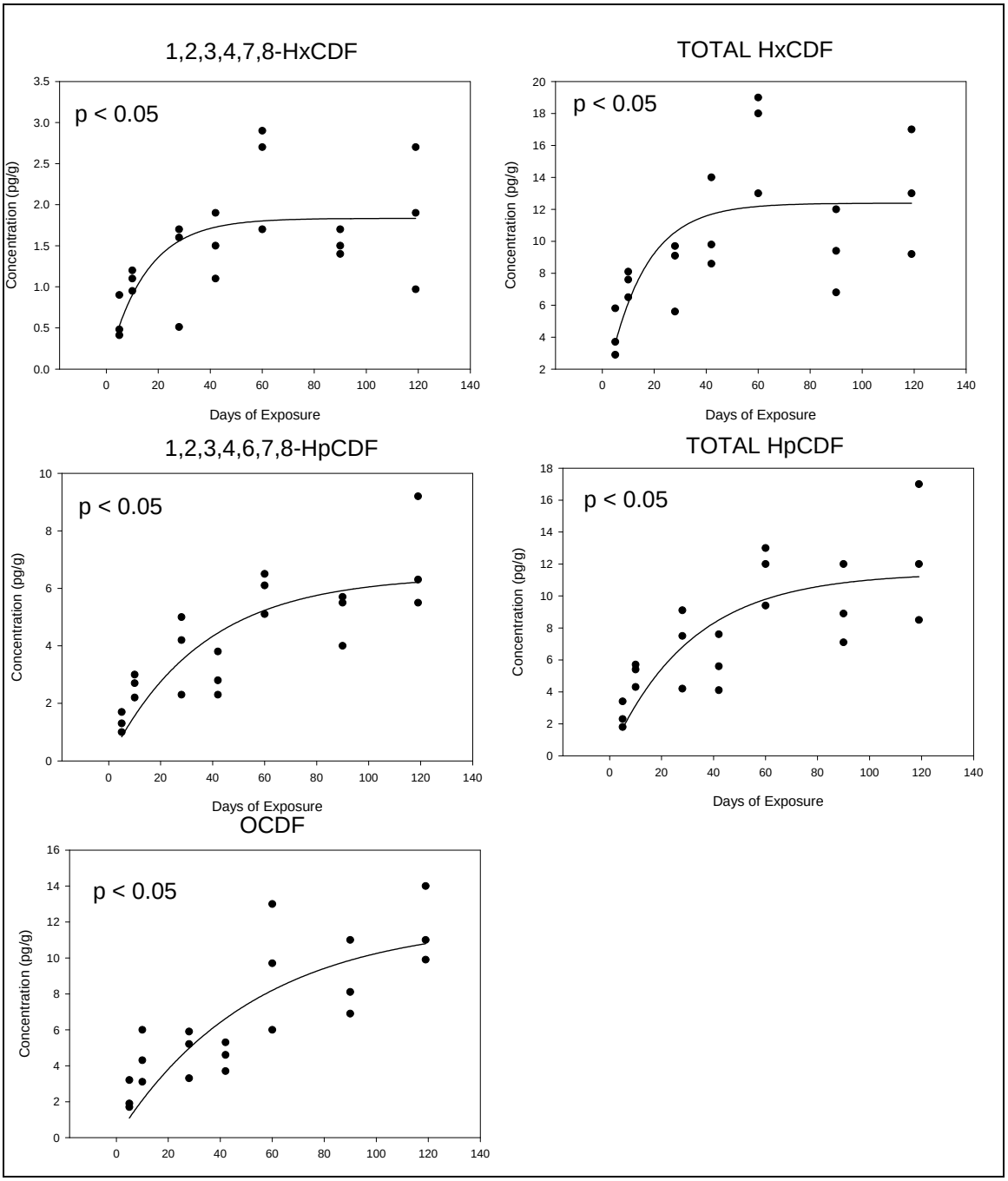

Figure D7. (Sheet 3 of 3).

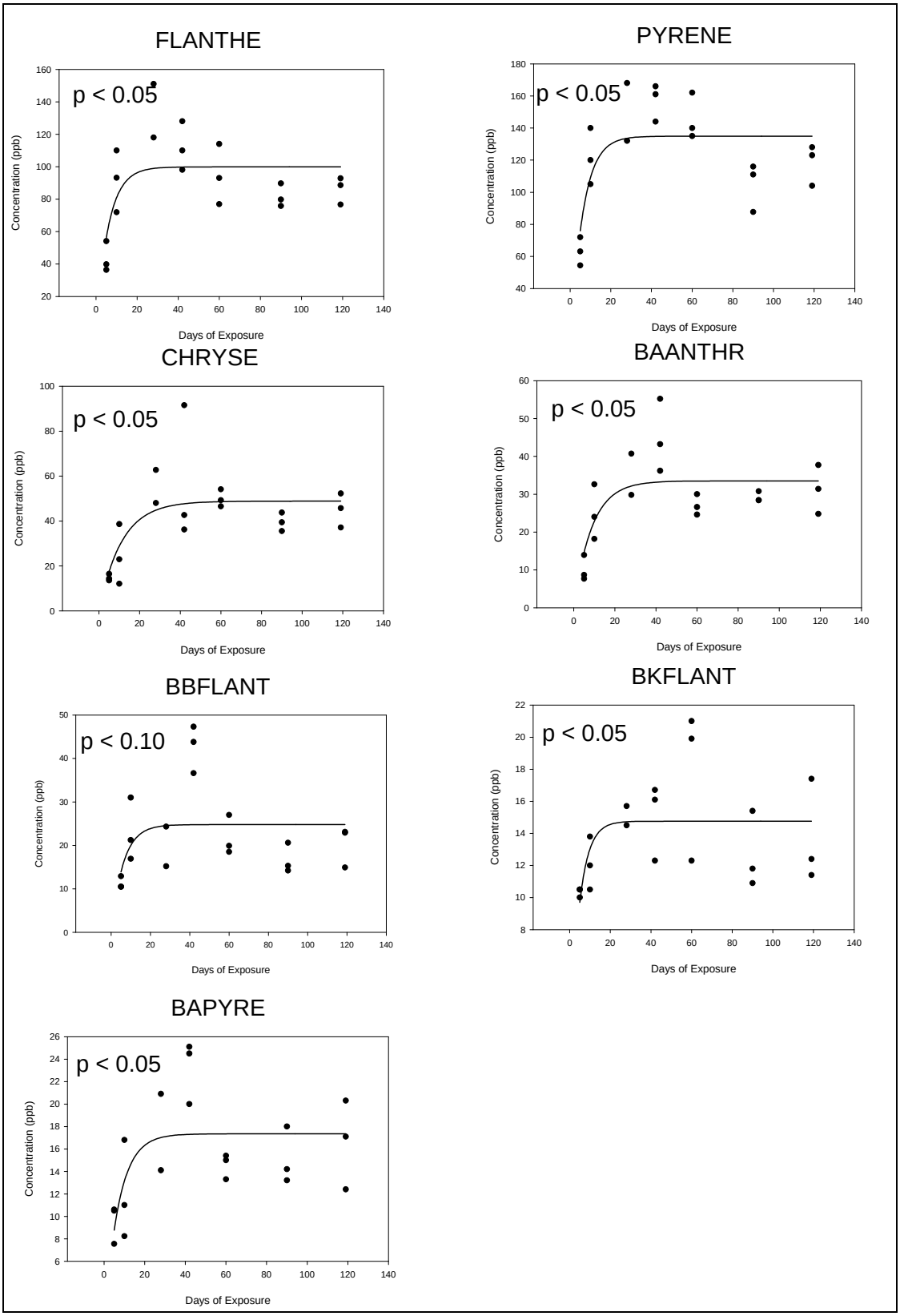

Figure D8. Uptake curves for *Macoma nasuta* exposed to PAHs in the Newark Bay sediment.

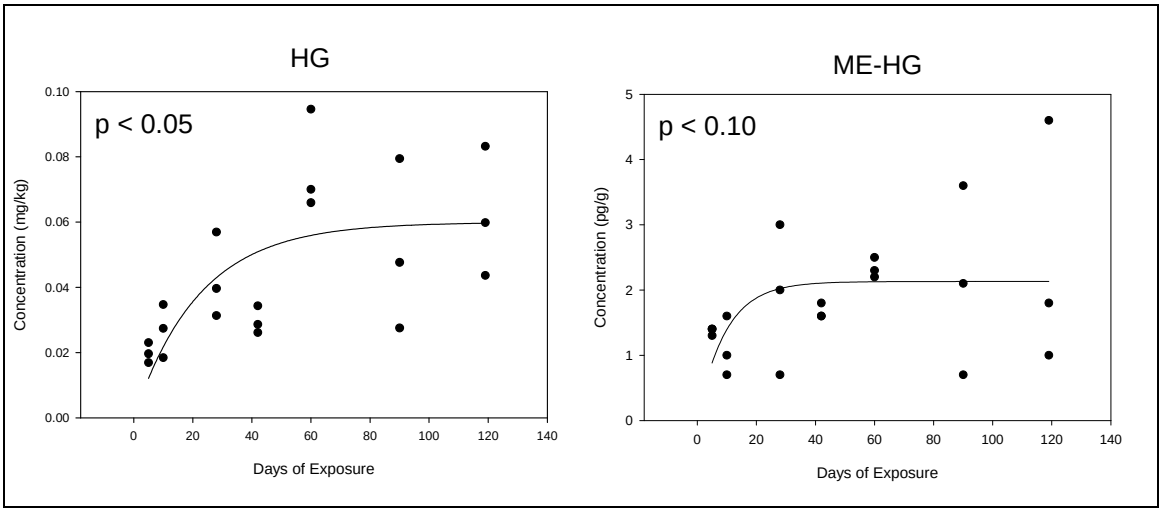

Figure D9. Uptake curves for *Macoma nasuta* exposed to mercury and methyl mercury in the Newark Bay sediment.

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14. ABSTRACT

Risk assessment of contaminated sediments often involves quantification of compounds in tissues via laboratory bioaccumulation exposures of benthic invertebrates. However, the standard 28-day exposure duration may not be adequately long for some compounds to reach steady state, defined as a stable concentration in exposed organisms. Steady-state tissue residues can be estimated using uptake and elimination rate constants. Experiments were conducted using two marine sediments from New York Harbor to assess bioaccumulation of PAHs, PCBs, chlorinated pesticides, dioxins, and Hg by sampling tissue during seven successive time points over an exposure of 56 days for the polychaete worm *Nereis virens* and 119 days for the clam *Macoma nasuta*. Exposure time required to attain steady state was organism and compound specific. Generally, *N. virens* tissues reached steady state more rapidly and accumulated higher contaminant residues. *Nereis virens* attained apparent steady state within roughly 28 days for PAHs, Hg, and most PCBs, but longer exposure was needed for some dioxins and pesticides. Steady state in *M. nasuta* was generally attained after 28 days of exposure for most compounds (some times after 100 days). Thus, some 28-day tissue residues may underestimate bioaccumulation and subsequently risk to benthos and higher trophic level organisms. The results of this study allow development of site-specific correction factors for estimating steady-state residues from 28-day exposures.

15. SUBJECT TERMS

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Contaminated sediment
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Macoma nasuta
Nereis virens
Steady state
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